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16. Abstract
This report summarizes the results of a study to design, develop, and implement a 3D/4D Area Navigation System for increasing aviation system capacity in the terminal area. Varying degrees of ATC and airborne system capability were assumed. The concepts developed are compatible with mixed airborne equipment capabilities.

The 3D terminal area procedures should result in reduced ATC communications through the use of 3D STAR's for nominal profile definition. Reverse fans and base offsets are used for impromptu path modifications. Increased safety should result by maintaining navigation in the cockpit. The 4D procedures rely on a computer aided ATC metering and spacing system. The use of RNAV STAR's is expected to substantially improve the M&S algorithm development, controller interface design, and pilot tracking accuracies.

The final avionics design has the capability for emulating two types of avionics equipments: one representing a minimum capability leg-at-a time, station referenced RNAV system and one representing a sophisticated route orientated, geographic referenced RNAV system. Real time cockpit simulations were performed to determine the adequacy of the pilot interface design and the performance capability. The system has been delivered to the FAA for actual flight testing.

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Preface

This report presents the results of a study to design, develop, and implement a family of area navigation systems suitable for 3- and 4-dimensional time control. Two systems representative of minimum capability and more sophisticated RNAV equipment were emulated. The systems were configured for use primarily in a terminal area environment with and without computer aided metering and spacing capability. The system has been delivered to FAA NAFEC for flight testing.

The Contracting Officer's Representative for the research and development program was Mr. Paul Rich of the Systems Research and Development Service, Federal Aviation Administration. His assistance was invaluable both in the development of the design and in structuring this report.

The authors also wish to acknowledge the work of Messrs. Larry H. Hogle, Robert J. Rudig, and Jay Prediger who were responsible for the programming, design verification, and system refinement.

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Introduction and Summary

Area navigation has been the object of recent renewed interest, both for use in the Continental US (CONUS) airspace and in more remote areas such as South America and Africa. In a certain sense, use of area navigation by the air carriers has been quite common when one considers oceanic flights where no ground based navigation aids exist. The ability to fly point to point was inherent in these guidance schemes, and the efficiency of direct flight paths was readily attainable. This has not been the rule in CONUS where IFR flight along VOR radials has been the standard for some time.

In CONUS, sufficient navaids were created to allow near direct routes between heavily trafficked population centers. Navigation outside these areas necessitates dog-leg flight paths which, on the average, did not result in too great penalties to the air carriers as the legs connected city pairs served in many cases by the flight.

More recently, the benefits of area navigation are being recognized by all users of the airspace. Several factors have brought about this change. Increased fuel costs have made all operators more sensitive to the route length savings possible with direct flights. Increased use of larger aircraft over extensive route lengths, without stopovers, has reduced the tolerance for flying intermediate legs. Perhaps most important has been the growth in business aviation flying into areas not directly connected by the high altitude airways and/or into airports not equipped with local VOR/DME stations. Direct flights from origin to destination are as natural and desirable for these users as they are for oceanic flights.

The benefits of area navigation can be felt not only by considering efficient direct flights, but also by considering the potential increases in airspace capacity. The present ATC capacity limitations were felt in the late 1960's before the introduction of wide body aircraft and the overall business recession. The congestion was most acute in the terminal areas; however, congestion was also being felt leading to the terminal areas.

At this time, the Air Traffic Control Advisory Committee was organized by the US Secretary of Transportation to examine the role of technology in solving the capacity constraints. Computer aided metering and spacing techniques were recommended for increasing terminal airspace capacity. Increased use of area navigation routes with parallel offset routes were recommended for increasing en route airspace capacity (ref 1).* It was obvious that this approach was more cost effective than adding additional VOR/DME stations whenever and wherever additional routes and/or capacity were needed.

The air carrier and business aviation communities continued to lead the growth of area navigation during this period. Their efforts led to the development of two families of navigation equipment -- sophisticated area navigation systems capable of interfacing with inertial sensor systems and a proliferation of "station mover" systems interfacing solely with VOR/DME inputs. The former utilizes an earth referenced (latitude/longitude) grid system, whereas the latter utilizes a local range/bearing or along-track/crosstrack reference system whose origin is offset some reference range and course from the navaid being tuned.

*See list of references in section 7.

Both types of equipment are useful in those areas where minimal ATC interaction is required. The sophisticated RNAV systems coupled to triple inertial sensor systems are highly cost effective in comparison to triple inertial navigation systems. The minimum capability systems are effective for VFR flight into uninstrumented and uncontrolled airports. The major technical limitations were the cost of the sophisticated systems where inertial complementation is unnecessary; the heavy workload for the station mover systems where navaid switching was plentiful.

The benefits of RNAV in CONUS operations requiring ATC interaction still remained difficult to achieve. A joint FAA/industry RNAV Task Force was established in 1972 to determine the role of area navigation in the National Airspace System (ref 2). A design concept was developed that included an orderly transition to RNAV implementation. Concepts requiring design validation were also addressed. Among the more important research and development activities requiring further investigation were a study quantifying the payoff benefits to the user and the ATC system, flight test evaluations of the capability of 2D and 3D RNAV systems to meet the reduced route width requirements, and a 4D design development and evaluation effort to determine if 3D and 4D concepts could be used to increase capacity in the terminal area.

The payoff study was completed in 1974 (ref 3). The study centered on the use of RNAV in the high altitude enroute areas and in six major terminal areas. The study concluded that user benefits in a charted high altitude structure were available then (1974), with 2D terminal area benefits achievable when a sufficient percentage of aircraft is RNAV equipped to warrant changing to an RNAV terminal area design. Estimated savings in 1972 dollars were found to be about $27 million for flights into the 6 terminal areas studied and $30 million in the charted 2D high altitude enroute airspace. Contrary to initial opinions, a mixed VOR/RNAV environment did not increase controller workload; moreover, use of RNAV reduced communications. The study concluded that increased terminal airspace capacity can be achieved economically through the flexibility provided by RNAV designs, in particular by establishing nominal RNAV SID's and STAR's.

Flight investigations concerning the capability of 2D and 3D RNAV systems to meet the route width requirements of ±2.5 nmi enroute and ±1.5 nmi in the terminal area were undertaken at FAA NAFEC in fiscal 1974 (ref 4). The adequacy of root-sum-square (RSS) method of error budgeting to arrive at the route width was also examined. A Collins ANS-70A system was leased by FAA for the flight investigation program. The tests indicated that the proposed route widths could be met with present RNAV technology. The RSS method was shown to be somewhat inaccurate but always on the conservative side.

The successful resolution of the 2D and 3D R&D questions coupled with the cost benefit advantages led to the issuance of the FAA policy statement on RNAV in January of 1977. The FAA has now gone on record as endorsing area navigation in the enroute and terminal areas and recognizes the benefits that RNAV offers to both the airspace users and the National Airspace System (ref 5). Among the action items discussed are the establishment of RNAV routes, SID's and STAR's, and the development of minimum performance standards.

Defining the minimum performance standards around present day RNAV equipments will prove to be challenging. The technological advances in the last few years have changed the concept of RNAV avionics equipment. Use of digital technology has removed the waypoint number as a classifier of low cost and high cost systems. Cost is more closely tied to input/output capabilities (including auxiliary sensors such as air data, omega/vlf), leg-at-a-time versus route navigation, and data base storage. Use of long-range navigation aids such as loran-C or omega in lieu of VOR/DME has significantly reduced pilot workload associated with manual systems as navaid station retuning is reduced or eliminated for

most flights. Processor requirements (and hence costs) are also reduced as VOR/DME data base problems are eliminated. Hence, use of these systems is becoming more attractive for long range direct flights. Specifying minimum performance standards is made difficult by the less well known nature of the signals in space (in comparison to VOR/DME).

A final area addressed by the RNAV Task Force needing further investigation was the role of area navigation in the automated time referenced metering and spacing concepts. These techniques are expected to reduce the buffer at the outer marker from 10-15 seconds to 5 seconds, thus offering the greatest potential increase in airport capacity (ref 6). The Task Force envisioned that while the present metering and spacing concept would initially be based on a vectoring mode, future development efforts would result in a 4D RNAV capability. They also recognized that no current 4D equipment was available and proposed a research program to identify, through quantitative analysis and simulation, the advantages/disadvantages of time reference navigation.

As part of this activity, the FAA in February of 1973 awarded a contract to Collins (DOT-FA72WA-3123, Three- and Four-Dimensional Area Navigation Study, Simulation and System Development). The purpose of the contract was to investigate the application of 3D/4D concepts in the airspace with particular emphasis on the terminal area. Various levels of ATC sophistication (from a manual to a completely automated system) were to be assumed. Adequate interfacing to various levels of navigation capability (from a Mark I to a Mark II type RNAV system) was required from all postulated ATC systems.

The initial study and cockpit simulation phase of the program was completed in June of 1974 (ref 7). Results of this phase validated the feasibility of utilizing a mixed environment of 3D and 4D procedures in the terminal areas. The following paragraphs summarize the significant conclusions:

Precise lateral flight path control could only be maintained if the pilot can respond to path deviations in a self-contained closed loop fashion. Terminal area approaches should be structured around 2D/3D RNAV STAR's with reverse delay fans and base or parallel offsets used for impromptu path modifications. This design concept is quite flexible, uses no additional airspace over that used today, is easily defined by the controller and executed by the pilot, and reduces communication workload.

Precise longitudinal control could only be maintained if the pilot can respond to path/speed deviations in a self-contained closed loop fashion. Nominal speed profiles can be included as part of a 4D RNAV STAR. Final delivery errors will then be less than that obtainable from any system controlling aircraft by means of verbal vectors from ATC, regardless of whether the commands are manually or computer generated. The time control concepts developed, analyzed, and simulated were largely compatible with the metering and spacing concepts under FAA development. However, the M&S algorithm must be modified to command total RNAV path assignments and approach gate arrival time rather than generate vector commands if the benefits of self-contained time control are to be achieved. Commanding reverse delay fans instead of forward delay fans appears to be the only flight path assignment change required. The latter fan is just as easy to communicate and monitor should vectors be required of non-RNAV equipped aircraft.

The real-time cockpit simulations revealed that delivery errors in a manual vector environment range from 10 to 20 seconds (1σ) which corresponds closely to that achievable in today's IFR environment. The timing errors associated with 4D closed loop time control were roughly half this value. The minimum capability leg-at-a-time RNAV systems were considered adequate for low speed aircraft. For high speed aircraft, a multiple leg RNAV system is required. Transition from VOR/DME to ILS/MLS guidance will require special

capture techniques to be utilized. If speed control is used on the final leg or during transition, simultaneous use of VOR/DME and ILS/MLS sensor data is required, necessitating the use of dual receivers. The control laws employed by RNAV systems for enroute guidance do not provide tight enough path tracking for final approach. Thus, with both ILS and MLS, RNAV enroute control laws must be modified to obtain satisfactory final approach performance.

Based upon the favorable results of the phase 1 effort, the FAA approved the second phase of the 3D/4D contract. The second phase consists of the final design, concept verification, and delivery of candidate 3D/4D systems.

The final design incorporated the changes recommended as a result of the first phase real time cockpit simulations. In particular, the time control algorithm was modified to allow loose longitudinal tracking early in the approach, and tighter tracking as the time control waypoint was approached. This resulted in lower tracking errors as the cyclic wind estimation errors did not have as significant an effect on speed commands as in the previous speed contract algorithm. The speed profile was also modified so that speed changes were always effected prior to a speed control waypoint and at the nominal rate of 40 kts/min. This eliminated the need to create additional speed control waypoints not needed for lateral path definition.

A base offset procedure was also incorporated to allow for impromptu base leg extensions. Finally, the capability to capture and track ILS beams while under RNAV (time control) guidance was included. With this system, terminal area time control experiments can be conducted anywhere from initial approach fix to touchdown.

As part of the design effort, a reduced capability 2D plus time control system was also developed. This system was intended to emulate the performance of a leg-at-a-time RNAV system. This system utilizes the identical 3D/4D hardware; the system changes were implemented through software.

The Phase II real time cockpit simulation effort verified that significant improvements in delivery accuracy over and above those recorded in Phase I can be achieved under suitable RNAV aided time control. Under autopilot control, tight 4D tracking is possible throughout the approach. The major contribution to delivery errors is the nonstationary nature of the prevailing wind. The 4D flight control errors are on the order of 3 to 5 seconds (1σ). These numbers do not include wind shear effects that were not modeled. The ability to predict and compensate for wind shear effects has not been determined. The preferred method of displaying time control command data is on the FAST/SLOW needle of the flight director. Display of commanded airspeed on the IAS indicator or CDU is mainly for cross-checking purposes. A ±10-knot full-scale deflection seemed appropriate.

Incorporating a base offset procedure greatly reduced pilot workload and blunder problems. Both 90° and multiple leg localizer intercepts with base leg extensions can easily be executed and flown using the base offset capability. In fact, the major design constraint is to standardize on a limited set of approach procedures and configure the RNAV approach consisting of nominal RNAV STAR plus impromptu modifications around these procedures.

ILS captures through the RNAV system are shown to significantly improve capture performance and reduce pilot workload provided proper operational techniques are utilized. The RNAV defined path must be made to intercept the ILS defined path in the presence of navaid error. If the paths do intercept, close-in ILS captures are ensured. Improvements in ILS tracking result from the ability to linearize the beam data. RNAV aided ILS captures with 90° intercept legs 5 nmi from threshold were routinely executed during the real time cockpit simulations. 90° captures 3 nmi from threshold are deemed unacceptable under manual or (single system) autopilot control as there is no margin for error.

The system was delivered to FAA NAFEC for flight testing. It is relatively certain that the tests will validate the feasibility and benefits of using 3D and 4D RNAV procedures in the terminal areas. A candidate avionics system will then exist which can utilize efficient 4D RNAV procedures from origin to destination. Final 4D design verification then awaits a suitable RNAV based metering and spacing system.

The final report documenting the second phase activities is divided into two volumes. Volume 1 contains a general description of the system, the background of its development, and results of the simulations. Volume 2 describes the detailed design and verification effort and the final software programs. The information necessary to install and maintain the system can be found in reference 8. The ANS-70A Pilots Operating Guide was also updated and is included as part of the final documentation effort (ref 9).

The contents of this volume can be summarized as follows.

Section 2 describes the 3D/4D system hardware complement; items to be delivered and items to which the system interfaces are addressed. Basic capabilities of the equipments are noted.

Section 3 describes the time control system characteristics. The system can emulate two different characteristics - a minimum capability 2D RNAV system utilizing time control only over the final leg to the time fix and a more sophisticated 3D RNAV system utilizing time control over the entire flight plan to the time fix. The functional description of the RNAV and time control capabilities is included.

Section 4 outlines the ILS control capability. Pilot operating procedures, data requirements, and mode availabilities are discussed. System limitations and performance monitoring capabilities are also provided.

Section 5 documents the real-time cockpit simulation undertaken to verify time control and ILS capture/tracking performance. Both autopilot and manual pilot experiments were flown with various approach geometries and differing speed control cues. Judgments regarding system performance and minimum requirements are offered.

The major conclusions are found in section 6.

2.1 GENERAL DESCRIPTION

The 3D/4D Navigation System is designed to provide the pilot with an airborne avionics system having the capability of providing flight path and speed computations for arrival at navigation points at prescribed times. The complete hardware complement to be supplied is shown in figure 2-1. The basic computations are accomplished in an 8564B-2X Navigation Control Unit Computer, which is a part of the Collins ANS-70A Automatic Navigation System. The ANS-70A uses inputs from air data and dual VOR and DME units for VOR-DME-VOR-DME calculations complemented with air data. In addition to the memory storage in the computer itself, additional flight data is provided in a tape data storage unit that can be loaded into the computer when routes are designated by the pilot. Pilot interface with the computer is provided by a CRT display and alphanumeric keyboard on the 813H-1A Control Display Unit located in the cockpit.

Although groundspeed and time to waypoint is a normal output of the ANS-70A, the 3D/4D system gives speed commands in several ways. The pilot may designate a specific desired time of arrival at a waypoint in the flight plan by keying in the time/waypoint data through the control display unit (CDU). If a 4D flight plan has been designated, the computer will predict the number of minutes that the airplane is early (or late) at the designated waypoint and display this information on the flight progress page of the CDU. A commanded airspeed is also displayed on the flight progress page, which will allow the pilot to null the time error.

Since the CDU is typically located in the center pedestal area of the cockpit, it may not be convenient to constantly view the CDU for speed commands while monitoring the conventional flight instrument group for altitude commands. For that reason, a speed error output is also provided to the attitude director indicator. This indication does not give the speed as a direct readout, but it is useful for small corrections when close to the required speed. In addition, an airspeed indicator is provided which displays commanded airspeed on the servoed "bug." The bug is driven by the commanded airspeed output from the NCU. Use of these displays will allow the pilot to observe all lateral/longitudinal command data on the primary flight instruments.

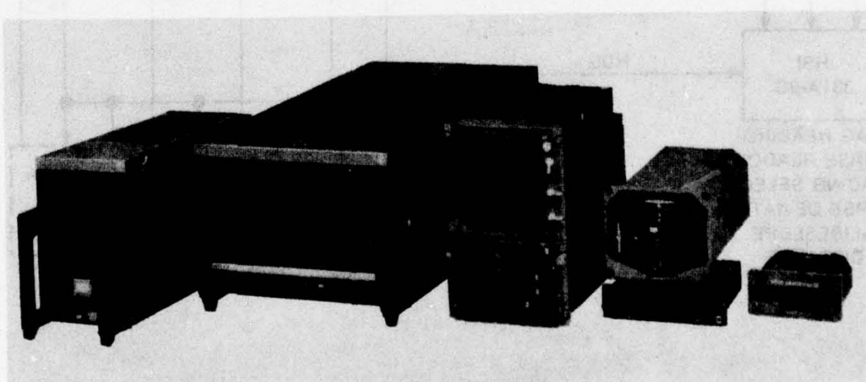


Figure 2-1. 3D/4D Equipment Complement.

2.2 SYSTEM DESCRIPTION

The block diagram shown in figure 2-2 represents the 3D/4D equipment complement described in this report. Items blocked out with dashed lines indicate equipments that the system interfaces but are not supplied with the system. The 3D/4D equipment was tailored to the FAA-NAFEC Gulfstream I and Convair 880 aircraft. As a result, the equipment complement for each aircraft is slightly different - both in deliverable equipment and in equipment to which the system interfaces. The 3D/4D system was designed to be compatible with both aircraft to test the system concepts on two aircraft with different flight characteristics.

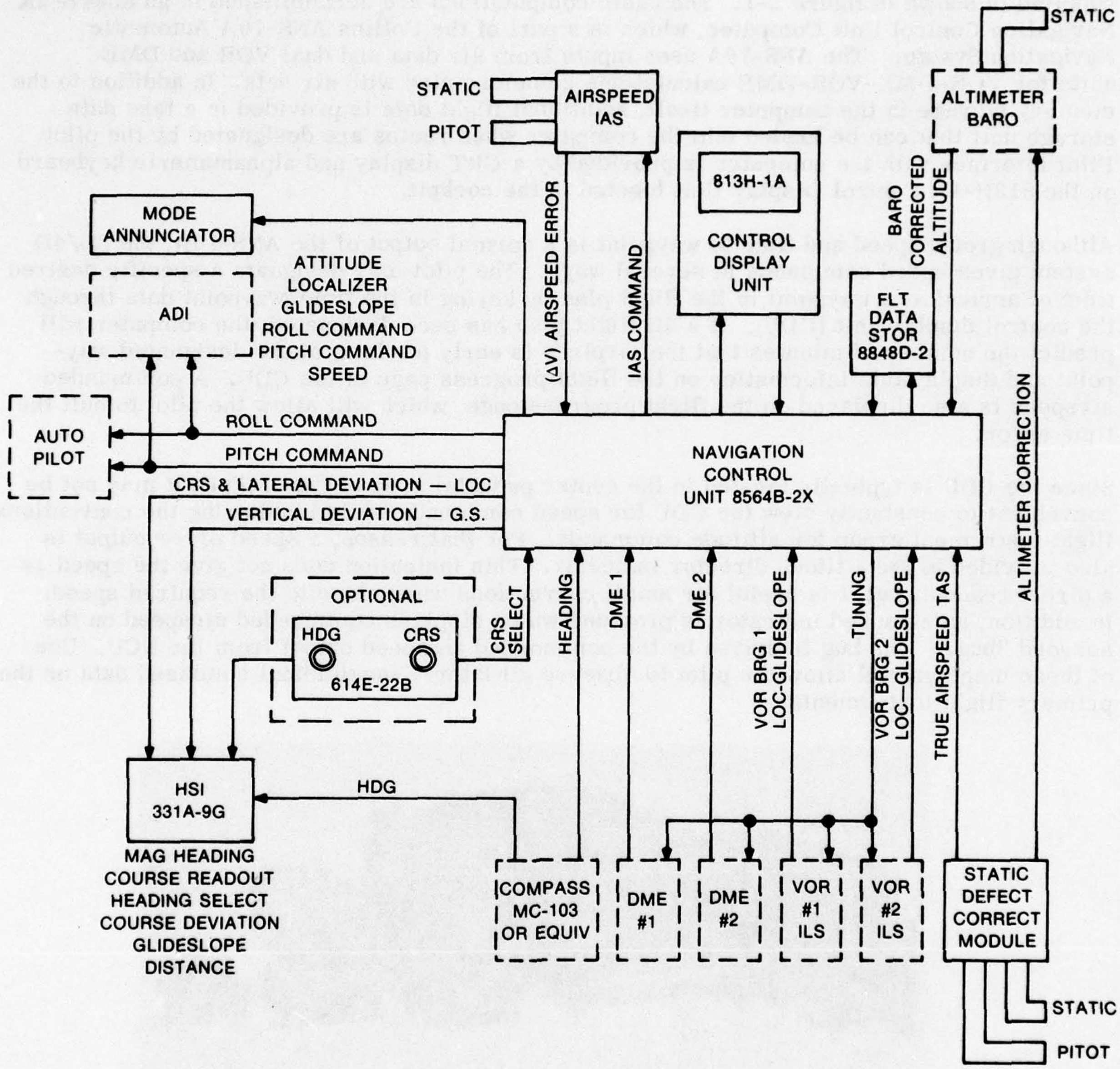


Figure 2-2. 3D/4D System Schematic.

2.2.1 RNAV System Complement

The ANS-70A is an ARINC 582 Mark II area navigation system, which features the capability for automatic navigation over the entire route of flight. The 8564B-2X Navigation Control Unit (NCU) (figure 2-3) is the central point for all sensor inputs as well as the source of the computations required for displays of selected course, course deviation, distance to waypoint, ground speed, time to waypoint, vertical guidance, ground-speed required, air-speed required, and steering commands in the lateral and longitudinal axes. Sufficient data storage exists in the NCU and flight data storage unit (figure 2-4) to store all US routes for high and low airways, all SID's and STAR's. The NCU will automatically select the best facilities available considering navaid type, reception distance, and relative geometry to the navaids.

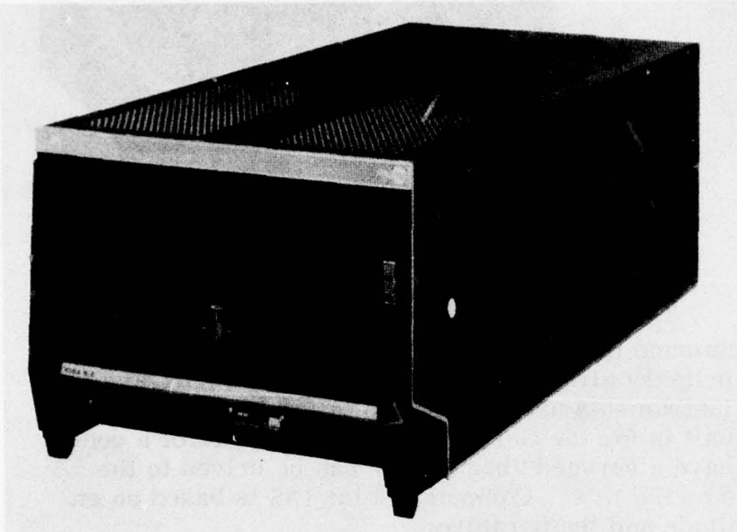


Figure 2-3. 8564B-2X Navigation Computer Unit.

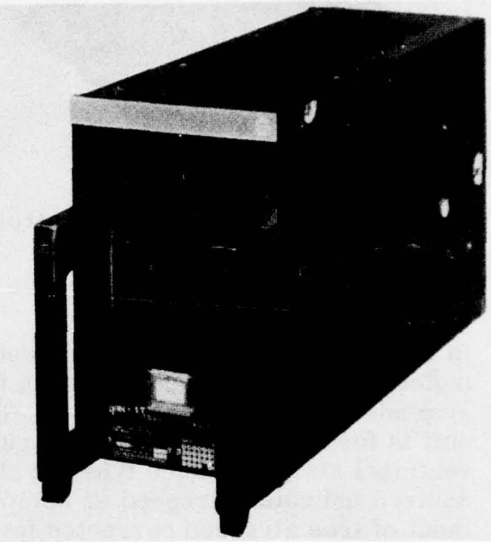


Figure 2-4. 8848D-2 Flight Data Storage Unit.

The pilot may select any one of pages of flight information that can be presented on the CRT of the control display unit (figure 2-5). In addition, the pilot may insert data relative to desired flight tracks and the computer will display course and steering information for any defined track. Groundspeed and enroute times are available as well as a readout of distance to any defined waypoint. Impromptu waypoints may be defined by insertion of bearing and distance from a known facility or waypoint as well as by latitude/longitude using the alphanumeric keyboard of the CDU.

2.2.2 Altimeter Complement

In addition to the inputs from the VOR-DME receivers and magnetic compass system, air data sources are provided for barometric altitude and true airspeed. The altimeter provides barocorrected altitude data to the NCU in the form of course-fine synchro data. An example of an altimeter of this type is shown in figure 2-6. Additional outputs are available for transponder altitude reporting and altitude rate, if needed for other systems.

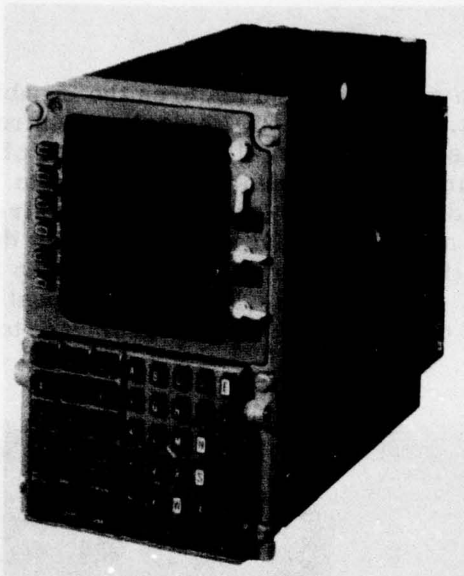


Figure 2-5. 813H-1A Control Display Unit.

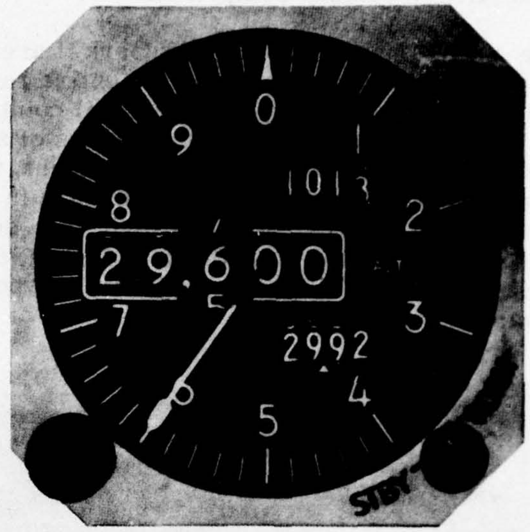


Figure 2-6. Encoding Altimeter.

2.2.3 IAS Complement

In this system an indicated airspeed command is also provided to the pilot on the airspeed indicator, since this instrument is the primary airspeed indicator which also portrays the airplane's peculiar speed limits. The instruments used are shown in figure 2-7. The left unit is for the CV-880, while the right unit is for the G-I. The instruments are of a conventional airspeed/mach type but also have a servoed "bug" which can be driven to the desired indicated airspeed as computed by the NCU. Computation for IAS is based on an input of true airspeed corrected for altitude and temperature.

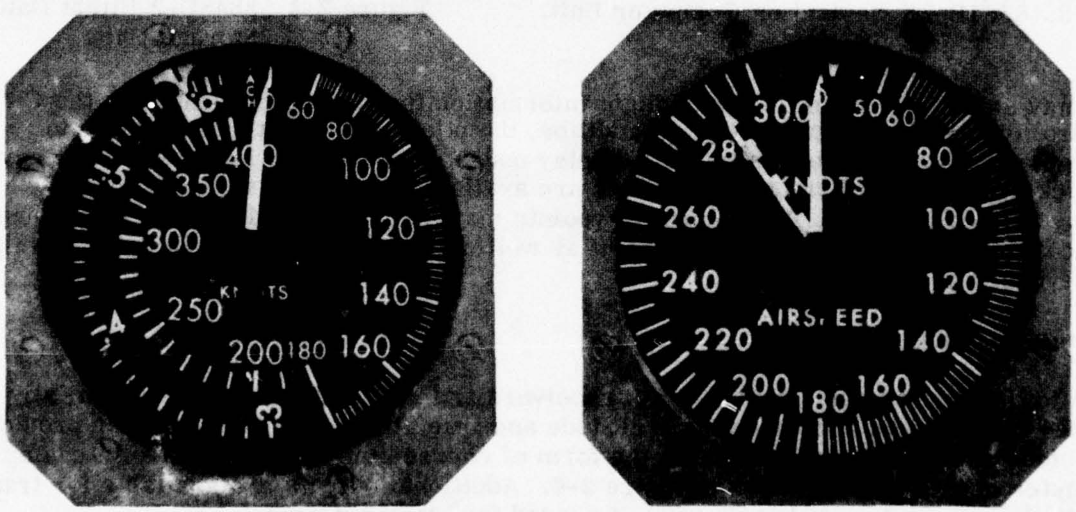


Figure 2-7. IAS Instruments With Servoed Command Bug.

2.2.4 TAS Computer Complement

The 8564B-2X computer utilizes an AC TAS signal. The Intercontinental Dynamics Corporation Static Defect Correction Module (SDCM) type 422-18152-900 series is provided for this purpose (figure 2-8). The SDCM is normally used in higher performance aircraft to correct the air data static source for errors that become excessive at higher speeds. This unit also provides a true airspeed output which is utilized in the 3D/4D system in the time control calculation as well as in the wind calculation.

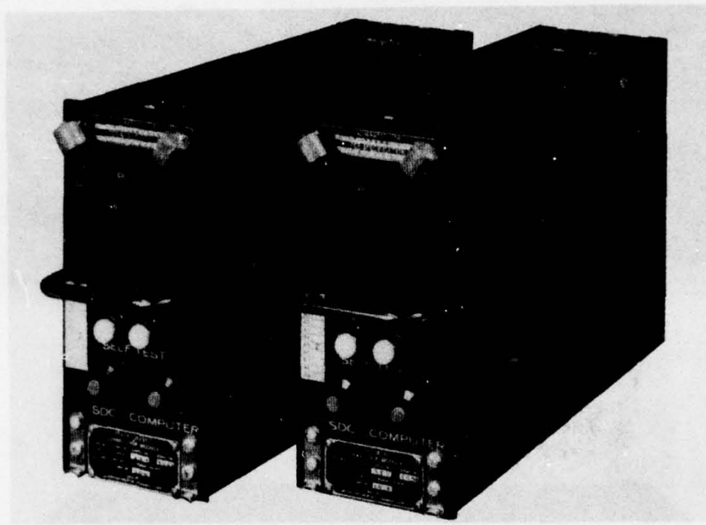


Figure 2-8. TAS Computers.

2.2.5 HSI Complement

The horizontal situation indicator (HSI) used with the 3D/4D system is of the servoed course card type typically used with stored/computed course area navigation systems. The type utilized in the G-I is the Collins 331A-9G Course Indicator as represented in figure 2-9. The CV-880 installation utilizes a Collins 331A-8A shown in figure 2-10. The indicators are quite similar. Both indicators contain servo positioned course selection, heading selection, and automatic bearing pointer similar to an RMI type indicator. Magnetic heading is read under the lubber line at the top of the rotatable card, which is positioned by inputs from the magnetic compass system. (True heading may be displayed if available from appropriate source such as an INS system.) Selected course is indicated by the course arrow and its position as read against the rotatable card. On the 331A-9G, the course is also displayed by a counter in the upper-right-hand corner and is a repeat of the indication shown by the course arrow. Deviation from selected course is indicated by the deviation bar and distance from the center of the instrument. In the 3D/4D system each dot represents 1 nautical mile linear deviation - or 2 miles from center to full scale. When using the instrumentation for an ILS approach, the course deviation data is changed to provide angular localizer deviation data. Vertical deviation is normally presented on the side of the instrument. During an ILS approach, the data is replaced with angular glideslope deviation data. Distance to the waypoint is shown as a digital readout in the upper-left corner of the instrument. The TO-FROM indicator is a broad triangular shape meter movement that appears from behind the center mask to indicate whether the aircraft is flying inbound or outbound from the selected waypoint.

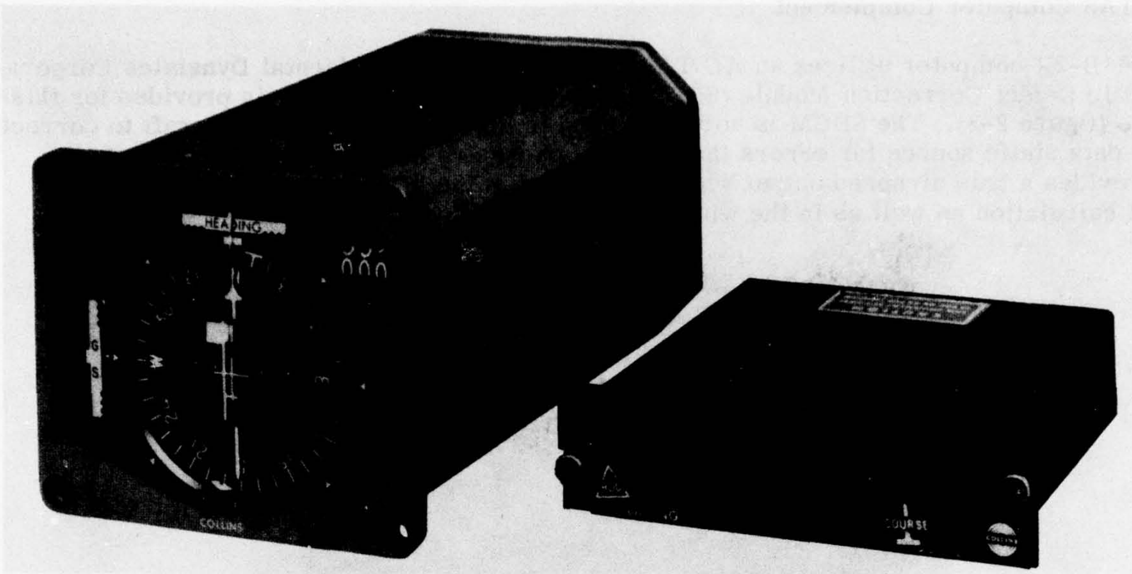


Figure 2-9. 331A-9G HSI With 614E-22B
Remote HDG/CRS Select.

Figure 2-10. 331A-8A Horizontal
Situation Indicator.

2.2.6 Remote Course/Heading Selector

A means of setting heading and course when flying via conventional (non-RNAV) navigation is provided by the remote manual control shown in figure 2-9. The unit also provides a manual analog course setting capability for a manual RNAV system emulation. The controller is typically located in the center pedestal of the aircraft adjacent to other flight director and autopilot controls within easy reach of the pilot.

2.2.7 Attitude Director Complement

The attitude director indicator shown in figure 2-11 is a Sperry type HZ -6F similar to the one available on the NAFEC G-I. Figure 2-12 illustrates the Collins ADI available on the CV-880. As in the case of the HSI's, both units have similar capability for displaying the required 3D/4D commands. In this instrument aircraft pitch and roll attitude is shown by the relationship of the aircraft symbol against the attitude sphere, which is positioned by outputs from a remote vertical gyro. The speed deviation is used to display the speed error from the IAS instrument and thereby gives the pilot a means of making small corrections of speed without having to divert his attention from the basic flight instrumentation group. Steering commands to intercept and maintain selected course and vertical path angles are driven by steering outputs from the navigation control unit computer. Similar steering commands are directed to the autopilot for coupling to the selected flight path.

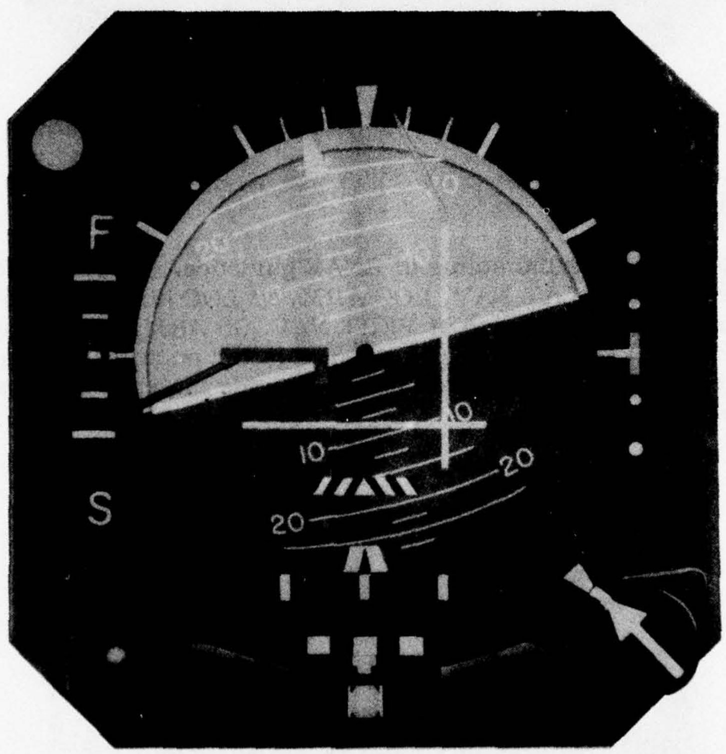


Figure 2-11. HZ-6F Attitude Director Indicator.

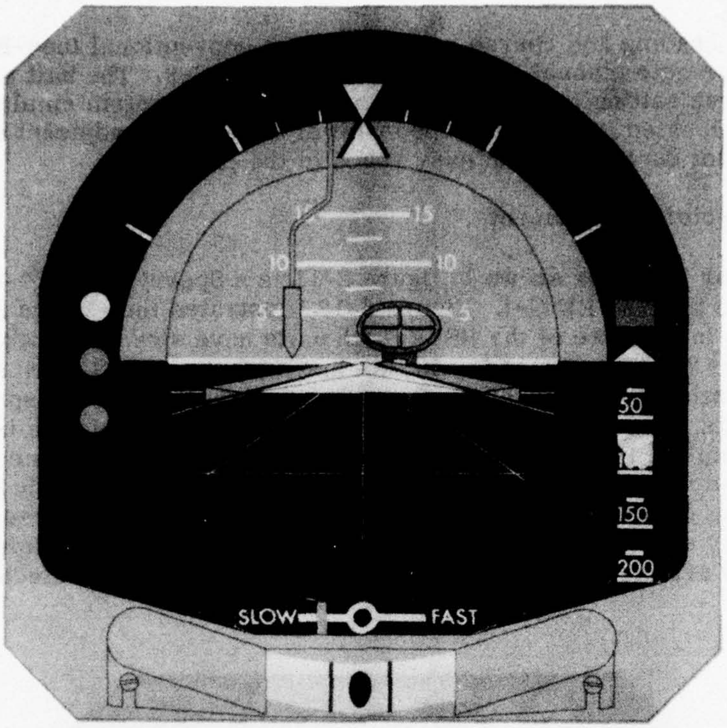


Figure 2-12. 329B-8R Attitude Director Indicator.

2.2.8 Mode Annunciator

The mode annunciator indicates the status of RNAV guidance. Lateral guidance is indicated by the presence or absence of LAT NAV, LOC ARM, or LOC displays. Longitudinal guidance is indicated by the presence or absence of VERT NAV, GS ARM, or GS display. A totally blank display indicates lack of RNAV guidance. The latter occurs for example when the RNAV system is not engaged (figure 2-13). Test buttons provide the capability to test indicator operation at any time during flight.

Figure 2-13. 327J-6 Mode Annunciator.

The mode annunciator incorporates prismatic electromechanical annunciators (PEA) for message display. Each PEA is a three-sided prism with two sides used for messages and the normal state blank. The messages are brought into view by energizing associated solenoids. LAT NAV is displayed when VOR/DME based RNAV guidance is utilized; it is not displayed when flying localizer or VOR conventional navigation. Analogous logic is used for the display of VERT NAV. LOC ARM (GS ARM) is displayed when the system is armed for localizer (glideslope) capture through the 3D/4D system. LOC (GS) is displayed when capturing or tracking localizer (glideslope) through the 3D/4D RNAV system.

3.1 PHASE 1 DESIGN PHILOSOPHY CONCEPTS

The Phase 1 design effort reviewed the present ATC terminal area procedures and examined the procedures proposed for future RNAV and metering and spacing terminal area environments. The analysis of the latter procedures concluded that the most effective (lowest workload, lowest confusion, and greatest capacity) future terminal area environment should consist of both RNAV and computer aided metering and spacing. It was further concluded that the currently proposed metering and spacing tracks are difficult to fly and hence additional controller monitoring and corrections are required. A flight path assignment change would correct these problems.

The recommended terminal area design would allow for a graceful implementation of various levels of RNAV and metering and spacing sophistication. A review of the 4D terminal area design configuration is given below.

3.1.1 Final Delivery Errors

The final delivery errors have a significant impact on terminal runway capacity in an IFR environment. The separation between successive aircraft must be great enough to ensure that the separation standards are not often violated. If the delivery errors are great, a large buffer distance must be provided, thereby reducing capacity. By reducing the delivery errors a smaller buffer is required, thereby increasing landing capacity. The often quoted quantitative benefits of 10 to 30 percent with computer aided metering and spacing can be deduced as follows:

The average spacing along the final path consists of the minimum separation standard (presently 3 nmi neglecting wake turbulance rules) and a buffer zone to allow for position and relative velocity uncertainties. The width of the buffer zone is set so that the probability of violating the minimum separation standard is low. The situation is typically analyzed by measuring the variance of interarrival times of aircraft and assuming an interarrival distribution and an allowable probability of violation, ρ_V (ref 10, 11). The mean buffer width is then chosen to meet that probability of violation criterion. The situation is depicted in figure 3-1.

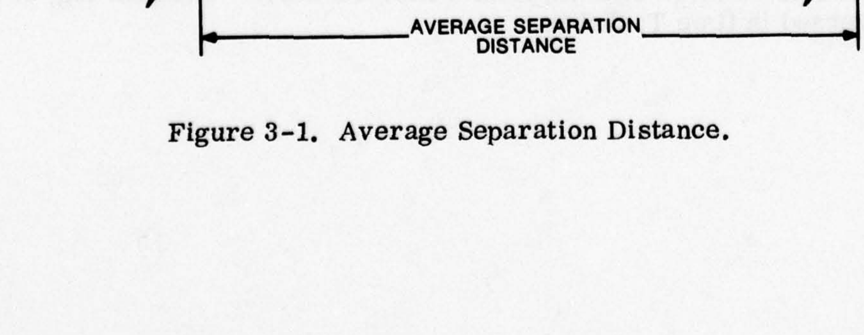


Figure 3-1. Average Separation Distance.

The violation probability is usually varied from 1 to 10 percent. Neither would result in acceptable levels of missed approaches. Those aircraft violating the standard are assumed to receive additional controller initiated commands to increase their relative separations. Assuming a Gaussian distribution, p_V equal to 10 percent corresponds to a buffer zone of 1.28σ ; p_V equal to 1 percent corresponds to a buffer zone of 2.33σ .

The present 3-mile separation standard results in a 70- to 90-second interarrival spacing for 120- to 150-knot approach speeds. An emperical value for the standard deviation of the inter-arrival time is 20 seconds (ref 6). Under computer control this value is expected to drop to 5 to 10 seconds (ref 6). Using the more conservative value of 10 seconds, the resulting 13 (1.3σ) to 23 (2.3σ) second decrease in spacing amounts to a 10- to 30-percent increase in runway acceptance rates, depending on the approach speed and the acceptable probability of violation.

Final delivery errors below 10 seconds should not be expected from a non-RNAV metering and spacing system. This conclusion is drawn from the delivery error diagram shown in figure 3-2. Assuming sufficient controllability exists so that the last ATC time control command can eliminate the initial position errors, final delivery errors will consist of ground speed estimation errors, position estimation errors, time from last update to the final fix, and aircraft ground speed. Integration of these effects is shown in figure 3-2. The solid vectored line indicates that with a ground speed error of 10 knots, a 4-minute update period, a position error of practically 0 results in a final delivery error of about 20 seconds at 120 knots. This situation corresponds to the errors experienced in today's terminal area IFR environment.

With automated metering and spacing, the only change expected is in the update rate (and in the accuracy of the commands whose effects are ignored in this diagram). A 2-minute update cycle could be used. This would reduce the final timing error to about 10 seconds.

A self-contained 4D RNAV system could continuously recompute the airspeed commands. However, assume that the pilot changes throttle settings at most once a minute. The 3D terminal area experiments verified that for a sophisticated RNAV system, position errors during approach are 0.15 nmi or less (ref 4). At an approach speed of 120 knots the final delivery error would then be about 5 seconds, roughly half the error obtainable with vectors commands. This situation is depicted by the dashed line in figure 3-2. Results using other parameters can also be determined.

3.1.2 Time Control Techniques

Two methods are available to alter an aircraft's expected time at a waypoint. These are a change in the nominal path and/or a change in the nominal speed. The extent of change required for a given timing error can be approximated as follows:

Under normal operating conditions, both the path and the times of arrival at the waypoints defining the path may be specified by assuming a (piecewise) constant velocity V. The time between waypoints T, is then D/V where D is the distance between waypoints. By assuming that the time to accelerate to a velocity is negligible, the speed changes, ΔV, required to maintain the scheduled arrival time can be determined as follows.

Assume that an aircraft arrives at a waypoint a time ΔT early. The next leg, of distance D, is nominally traversed in time T; that is,

$$D = VT$$

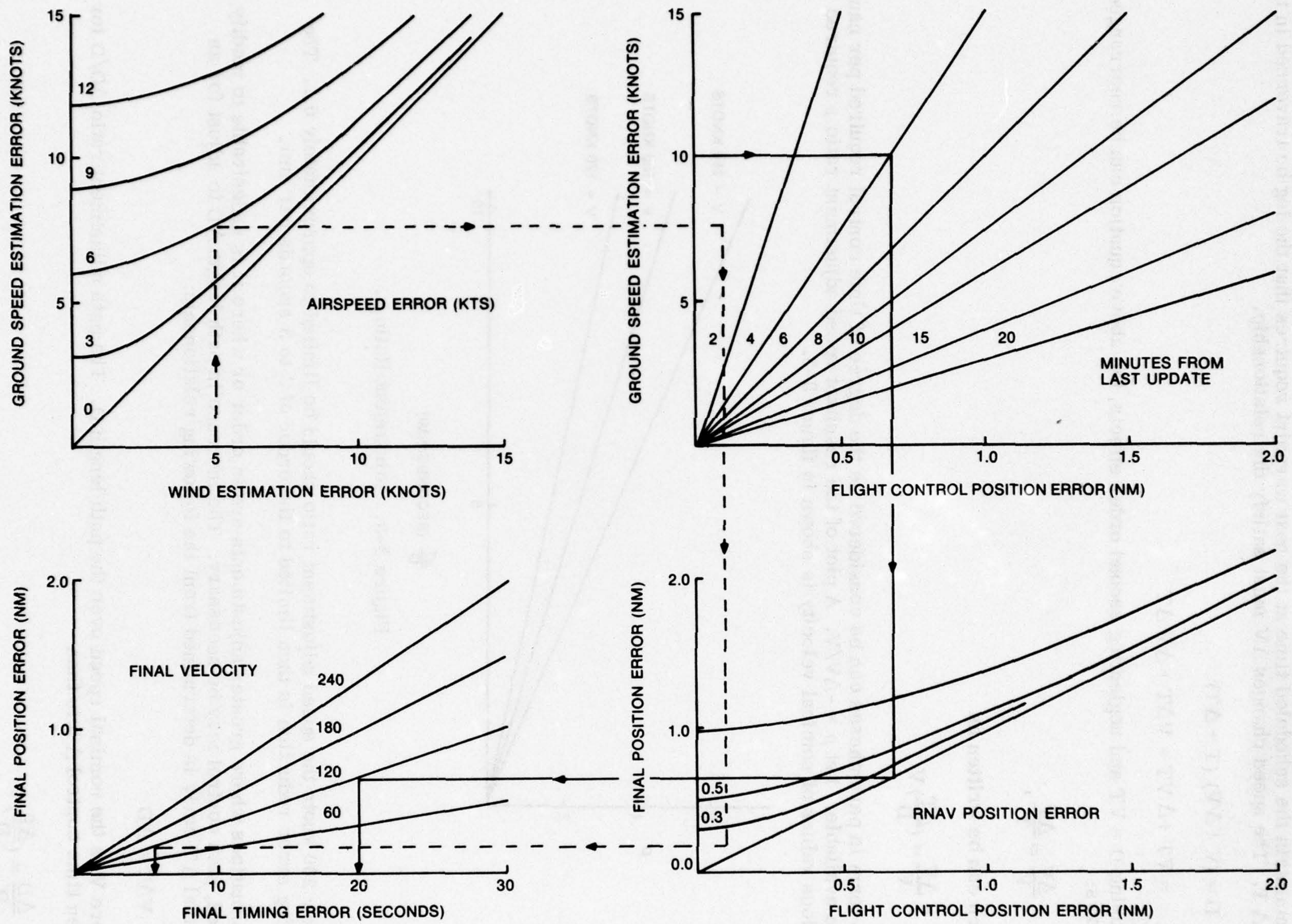


Figure 3-2. Final Position Error Computation.

To maintain the scheduled time at the next waypoint requires that the leg be traversed in time $T + \Delta T$. The speed changes ΔV must satisfy the relationship.

$$D = (V + \Delta V)(T + \Delta T)$$

$$= VT + \Delta VT + V\Delta T + \Delta V \Delta T$$

By using $D = VT$ and neglecting second order effects, the above equation can be rearranged as follows:

$$-\frac{\Delta V}{V} = \frac{\Delta T}{T},$$

which can be written as

$$-\frac{\Delta V}{V} = \left(\frac{\Delta T}{D}\right) V$$

The term in parentheses can be considered as the degree of time control required per nautical mile available. Let $\rho = -\Delta V/V$. A plot of the resultant speed adjustment ratio ρ required for various values of nominal velocity is shown in figure 3-3.

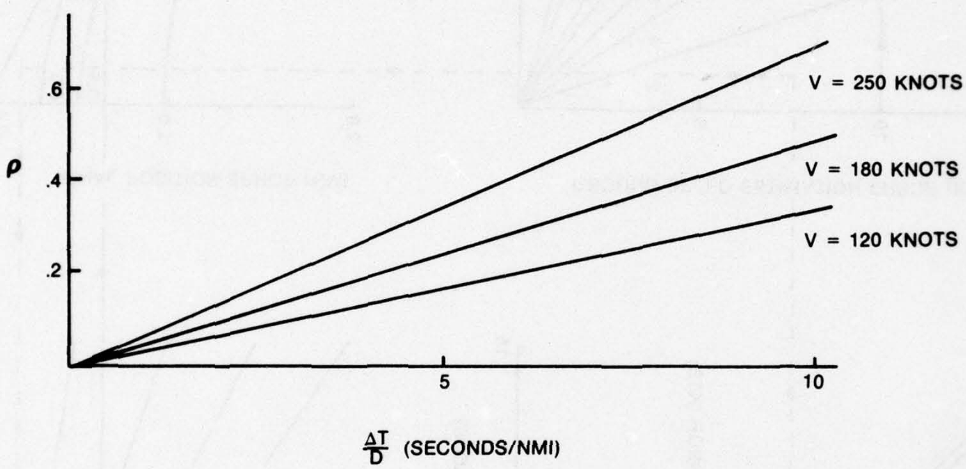


Figure 3-3. Adjustment Ratio ρ.

Below 200 knots the speed adjustment ratio should be limited to approximately 0.1. The timing error reduction is then limited to the order of 2 to 3 seconds per nmi.

In situations where greater adjustments are in order or where it is undesirable to modify speed, path control may be necessary. The increase in path length ΔD to adjust for an arrival ΔT early is determined from the following relationship:

$$V\Delta T = \Delta D$$

where V is the nominal speed over the path length D. The path adjustment ratio $\Delta D/D$ for a given time control ΔT is then

$$\frac{\Delta D}{D} = \left(\frac{\Delta T}{D}\right) V$$

which is similar in form to the speed adjustment ratio obtained previously. Hence, figure 3-3 may also be used to compute the required path adjustment with $\rho = \frac{\Delta D}{D}$. In this situation ρ is not limited to any value. Hence large changes in final delivery times will require changes from nominal path. Small changes can be effected by speed changes.

Several different control techniques can be used to effect the path adjustment. Many techniques are used by ATC today. In order to design avionics equipment that can readily effect impromptu path changes, it is imperative that ATC standardize on a limited set. Three methods are recommended that can easily be executed by most 2D RNAV equipment. Two methods can also be used by 4D time control systems. These are defined below.

The reverse fan is shown in figure 3-4. It is characterized by a single path out of a waypoint and a family of paths into a succeeding waypoint. The delay fan can be flown by all 2D RNAV systems in a closed loop fashion.

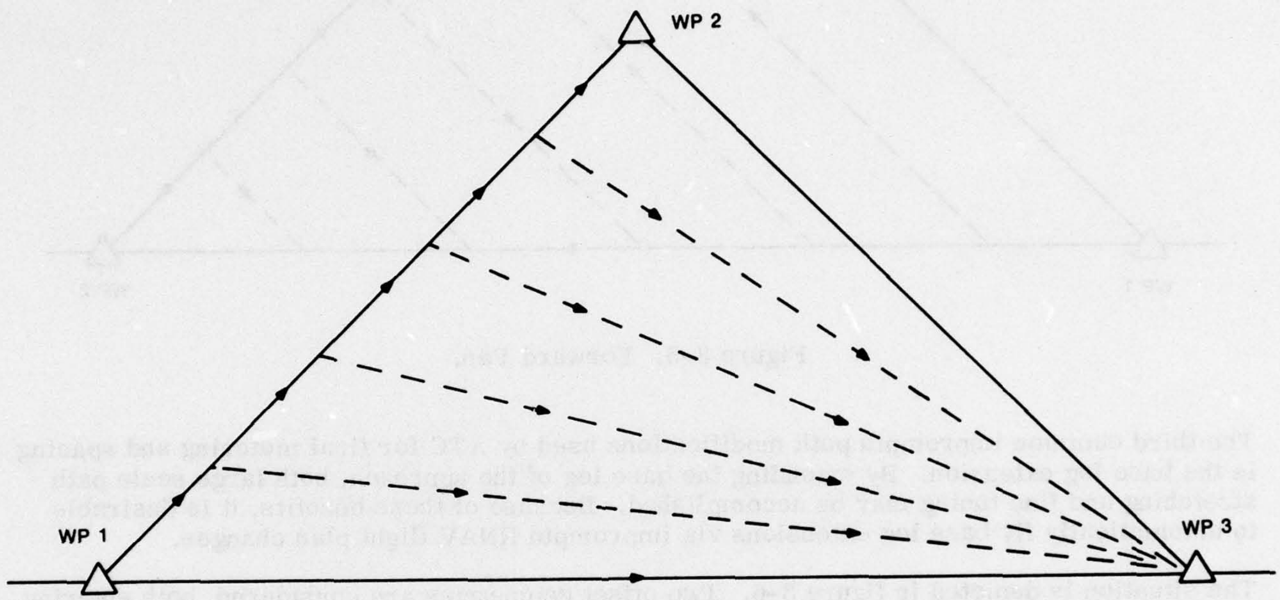


Figure 3-4. Reverse Fan.

The aircraft proceeds to waypoint 3 via waypoint 2 and turns direct-to waypoint 3 a specified distance prior to waypoint 2. Waypoint 2 is a designated delay fan waypoint. By inserting a turn point at the specified distance prior to waypoint 2, complete 4D closed loop control can be maintained along the delay fan. The path could also be commanded by commanding a heading (through the RNAV system) or large parallel offset out of waypoint 1 and then commanding a track direct-to waypoint 3 at the appropriate time. However, closed loop path control (that is, a specified ground track) would not be flown during the outbound leg.

Figure 3-5 illustrates a forward fan. It cannot readily be flown in a closed loop 2D or 4D fashion. At the appropriate time a heading or offset is commanded followed by a direct-to to waypoint 2. While it could be used for 2D or 3D applications, 4D self-contained time control cannot be accomplished until after the RNAV path is again commanded, as the duration of the offset leg is not known by the RNAV system.

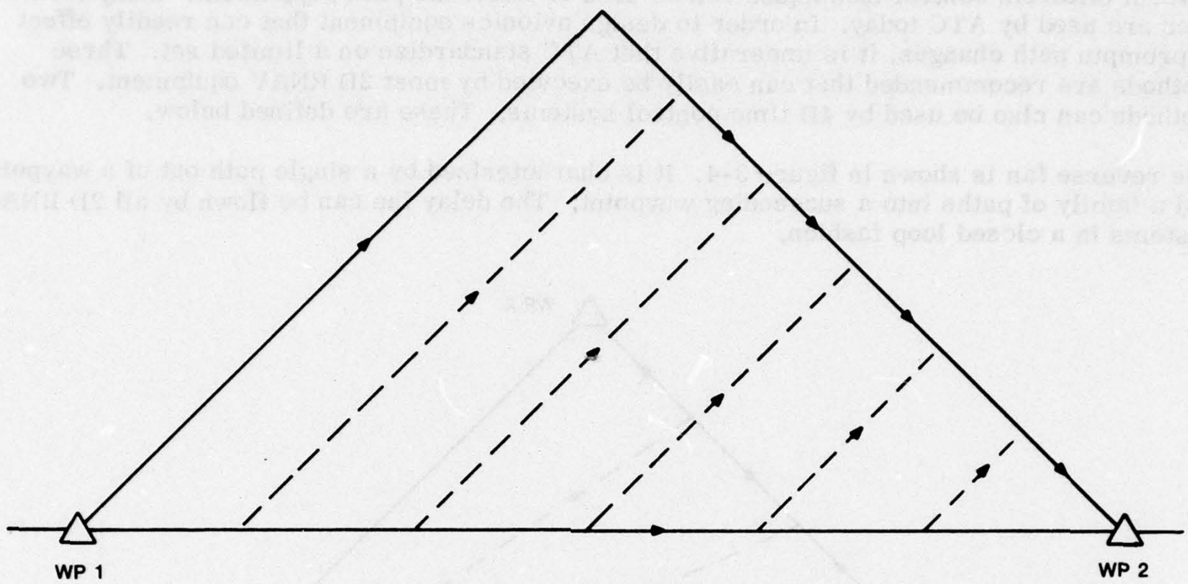


Figure 3-5. Forward Fan.

The third common impromptu path modifications used by ATC for final metering and spacing is the base leg extension. By extending the base leg of the approach, both large scale path stretching and fine tuning may be accomplished. Because of these benefits, it is desirable to automatically fly base leg extensions via impromptu RNAV flight plan changes.

The situation is depicted in figure 3-6. Two offset geometries are considered, both entering the base leg with a 90° turn. The first situation illustrates a shallow capture while the second illustrates a 90° capture.

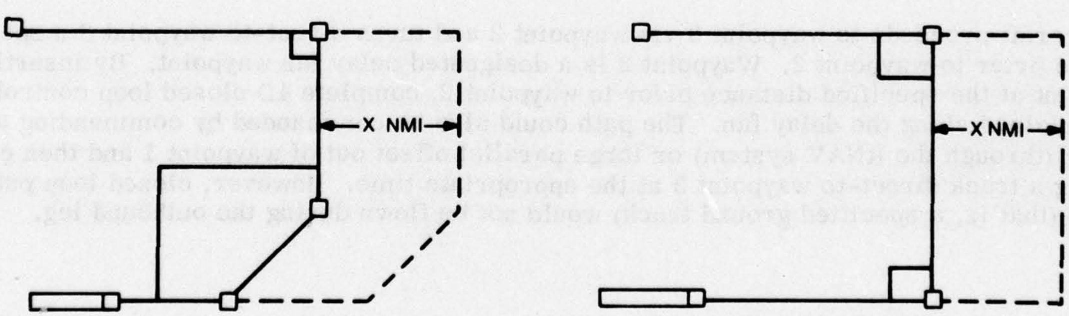


Figure 3-6. Base Offset Geometry.

For leg-at-a-time systems, the 90° capture is straightforward. An offset is commanded on the base leg. For the shallow intercept leg a second (different) offset must be commanded on the intercept leg whose value is the first offset times the sine of the intercept angle. The localizer leg must be captured when the distance to wayline is the base offset distance times the cosine of the intercept angle. Because of this complexity on shallow intercepts, the leg-at-a-time system should intercept the localizer leg flying a heading.

For multiple leg systems, a leg-at-a-time offset capability is required. Since this is not generally available, a new automatic base leg procedure should be defined. The procedure implemented has the following characteristics: The offset is entered at the base leg waypoint. An entry of a BXY.Z at this waypoint in the flight plan would offset the baseleg by XY.Z miles.

A limit of 20 nmi is imposed with a resolution of 0.1 nmi.

Several data reasonableness checks are also included. Attempting to enter the offset at any waypoint not meeting the above geometry is not allowed. Because of the intended application, base leg offsets and normal parallel offsets are mutually exclusive in flight plan definition. Canceling the flight plan geometry once a base offset course is entered is disallowed; the offset must first be canceled by the pilot. The only exception to this restriction is in the use of a "direct-to" procedure. A direct-to will cancel any offset.

3.1.3 ATC/Avionics Interaction

The greatest benefit to ATC capacity and system safety results from utilizing RNAV flight procedures with computer assisted time-of-arrival computations. The exact form of these computations is quite flexible. It would appear that the computer-aided RNAV time control system would monitor the airport acceptance rate, sequence aircraft on a (nearly) first-come-first-served basis, calculate the estimated times of arrival (including delays) of all aircraft in the system, and possibly aid in metering and spacing the aircraft. The latter task would include determining a departure time from the holding fix and assigning an arrival route to adjust for the remaining required delay. Since this task would require various sophisticated decision making capabilities in a computer, tasks most successfully performed in the past by the controller, the best man machine allocation of tasks is difficult to predict: a completely manual system would not take advantage of the rapid computational capabilities of the computer while a completely automatic system would still require the controller (and, of course, the aircraft pilot) to understand the computer decisions.

On the other hand, it would appear that the level of metering and spacing automation is not a dominant factor in the design of RNAV time control procedures and airborne equipment. Automation will affect the precision of the time control commands and thus affects total timing accuracy. However, the level of ground-based metering and spacing automation has no effect on how well the pilot can control his aircraft to meet the controller requests. What is of concern in airborne system design is the controller and pilot/aircraft command and response loop. Since the controller must understand the control strategy to be followed and communicate the pertinent information to the pilot, similar commands should be used in both manual and semiautomated metering and spacing environments. Efficiency, capacity, and safety may be improved with computer aiding, but airborne equipment design is essentially independent of the overall metering and spacing technique.

The basic airborne system must provide for easy insertion and execution of an ATC-assigned, delay free, RNAV arrival route and for impromptu modifications to that route to compensate for system delays. The delay is allocated between the time to be spent at a holding fix and the delay to be absorbed during the approach. The latter delay is used to specify the RNAV flight path modifications as delay fans, base leg extensions, and speed assignments. Nominal

speeds are assigned by including them in the RNAV STAR. Impromptu speed modifications would then be handled in the same manner as flight path modifications.

The aircraft's estimated time of arrival at a designated approach fix (initial, final, or intermediate) would be communicated to the pilot. The pilot could use this data to make minor airspeed modifications to assist in obtaining the expected time of arrival. Except for minor ad hoc variations to reflect changing conditions or "fine tuning," the entire a priori arrival route would be known by not only the controller but also by the pilot. The use of a nominal 4D RNAV STAR (3D fixed path plus nominal speed assignments) would limit communication to the STAR name; adjustments would then be by exception rather than by rule. Controller/pilot communication would be kept to a minimum. In addition, these exceptions need not be communicated at the precise moment of path adjustment, but at any time prior to the required modification, thereby reducing the possibility of improperly timed path modifications.

With these RNAV procedures, safety should be improved. Navigation would be retained in the cockpit even if short vectors off the RNAV route were necessary as along-track and cross-track position would remain meaningful. Extensive path adjustments by means of impromptu RNAV path modifications would not cause pilot disorientation. The aircraft could remain coupled to the autopilot, freeing the pilot for other duties. Finally, since flight path and flight path time from the holding fix are well known, the need for length in-trail spacing would be reduced. The necessary delay could then be absorbed in the higher altitude, more fuel-efficient holding areas.

3.1.4 Control Authority

While a great deal of flexibility exists in the nature of the 4D ATC and airborne systems, the authority to make the path and speed assignments must still be assigned. Certain 4D approach systems assume that ATC defines the nominal profile and assigns the time at the final fix (ref 12). The airborne system is allowed to alter both the nominal 3D STAR and speed profile to meet the scheduled arrival time at the fix. However, difficulties are envisioned for allowing this degree of avionics freedom. This type of on-board capability appears unnecessary and may even be dangerous in the event of airborne or ground based system errors as it is necessary that flight path assignments including speed be consistent for all aircraft in the area. This requires proper metering and spacing throughout the approach and not just at the final fix. Since monitoring of system performance is the responsibility of ATC, ATC must maintain knowledge of all flight paths. Aircraft/ATC flight profile verification is, therefore, required regardless of where the flight profile is chosen. Since ATC is responsible for time assignment (which requires knowledge of all aircraft and their potential path assignments) it is reasonable to assume that path assignments also be made by ATC to obtain nonconflicting flight profiles. If the revised times and impromptu path modifications are then communicated to the pilot, it would eliminate the need for a multiplicity of airborne equipments performing the same function with no apparent increase in system performance.

Because of these reservations about on-board flight profile selection, the analysis and simulation done in this program assumed that the entire flight profile, consisting of nominal 4D STAR plus path modifications and expected time at the time-fix, is assigned by ATC. The airborne system would attempt to fly this profile in a closed loop fashion. Flight path deviations would be sensed, displayed, and possibly corrected by the RNAV system. Speed deviations would be sensed by the time control algorithm; corrective action would be suggested. The level of sophistication of the time control algorithm would be tied to the accuracy and capability of the RNAV system. For example, a leg-at-a-time RNAV system would have speed commands only on the final leg. A multiple leg RNAV system would have speed commands throughout the approach.

3.1.5 RNAV Functional Characteristics

Several classes of RNAV systems were considered in phase 1. It was concluded that two classes of equipment would be representative of the performance achieved with a time control RNAV system. The two classes are representative of the avionic capabilities expected in sophisticated air carrier and minimum capability general aviation equipments. The distinction is not so much one of waypoint number, analog versus digital, 2D versus 3D etc, but more of automatic operation of flight plan parameters versus single real time modification of parameters for each flight leg. Table 3-1 lists some of the major class distinctions of the two levels of RNAV systems that were used as a basis for the time control system designs.

Table 3-1. RNAV Functional Capabilities.

RNAV CHARACTERISTICS	AIR CARRIER CLASS EQUIPMENT	GENERAL AVIATION CLASS EQUIPMENT
Route Definition		
Waypoint description	Alphanumeric ident, altitude, impromptu definition by LAT/LONG, BRG/DIST from WPT or navaid, ALT/FL.	BRG/DIST from navaid (2-D only)
Flight plan construction	By airport idents, company routes, SID's, STAR's, airways, navaids, waypoints, idents, LAT/LONG, BRG/DIST from navaids, altitudes and flight levels, impromptu headings, vertical speed/angle, holding patterns, and along-track offset waypoints.	BRG/DIST from navaid 1-20 preset waypoints
Waypoint sequencing	Automatic.	Manual
Course selection	Automatic (course to the "TO" waypoint is pilot editable).	Manual
Parallel offset	By route or impromptu with automatic capture and baseleg offset.	Impromptu with no capture guidance
VOR/DME tuning	Automatic station selection based on closest usable DME-DME pair. Automatic radio submode switching.	Manual (single VOR/DME)
DIRECT TO	Automatic course set with anti-overshoot compensation.	Manual course set

Table 3-1. RNAV Functional Capabilities (Cont).

RNAV CHARACTERISTICS	AIR CARRIER CLASS EQUIPMENT	GENERAL AVIATION CLASS EQUIPMENT
Position Determination		
Ground navaids	Dual VOR/DME.	Single VOR/DME
Position estimate	Optimal mixing of all position and velocity data.	Fixed filtering of single VOR/DME data
Velocity complementation	Heading/air data or INS.	Typically not
Data reasonableness check	Yes.	None
Graceful degradation for loss of position/ velocity information	Yes.	None
Wind estimation	Yes.	Typically not
Slant range correction	Automatic.	Automatic with manual entry of station elevation
Guidance		
Autopilot coupling	Yes.	None
Autothrottle coupling	Optional.	None
Heading-to-course captures	Automatic.	Manual
Offset course	45-degree capture.	Manual
Initial captures	Automatic.	Manual
Leg-to-leg capture	Automatic with turn anticipation as a function of course change and ground speed.	Manual
Procedure turns	Automatic.	Manual
Holding patterns	Automatic 3-sector entry, execution, exit. Standard and non-standard patterns.	Manual

Table 3-1. RNAV Functional Capabilities (Cont).

RNAV CHARACTERISTICS	AIR CARRIER CLASS EQUIPMENT	GENERAL AVIATION CLASS EQUIPMENT
Lateral maneuvers	Constant bank angle limit.	None
Vertical maneuvers	0.05-g constant acceleration captures.	None
Vertical speed	Yes.	None
Vertical angle	Yes.	Typically not
Annunciations, Special Messages and Auxiliary Data		
Lateral leg switch alert	Yes.	None
Vertical waypoint alert	Yes.	Typically not
Possible error in FLT plan	Excessive distance between way-points, extreme turn angles, etc.	None
Navigation mode downgrade	Yes.	None
Navigation/steering flag	Yes.	Yes
Failure monitors	Failures identified to LRU level plus on-board maintenance diagnostic.	RNAV validity warning/ flag, but no indication of failed unit(s)
Chart display	Option.	None
Auxiliary data	Additional data display such as wind direction/velocity, TIME/ DIST/BRG to any waypoint, digital display of crosstrack and vertical deviation, navaid idents, required vertical speed/angle.	Generally not available

The level of time control capability that is added to these area navigation systems is shown in table 3-2. The air carrier type equipment reflects the degree of sophistication and automation expected in a system for this user. The expected time of arrival is entered at any waypoint in the flight plan. Closed loop time control is to be exercised over the entire flight. The algorithm computes the required groundspeeds to meet schedule. Airspeed commands are presented which compensate for both winds and turns throughout the approach.

The general aviation system user is assumed to navigate at a leg-at-a-time basis. With only the arrival time at the time-fix communicated by ATC, closed loop time control is exercised only on the leg to the time fix waypoint. The required groundspeed is computed only when navigating to the time fix. Because of the requirement for velocity complementation of VOR/DME data to arrive at the desired 2D accuracies (ref 7) some sort of airspeed input (TAS, altitude corrected IAS, etc) is required. Hence winds can be estimated and the pilot can be issued a commanded IAS instead of merely a groundspeed. A detailed description of the two systems is given below.

Table 3-2. Self-Contained, Time Control Capabilities.

SYSTEM CHARACTERISTICS	AIR CARRIER CLASS EQUIPMENT	GENERAL AVIATION CLASS EQUIPMENT
Time		
GMT in NCU	Yes	Yes
Arrival time fix	Any waypoint	TO waypoint
Airspeed Commands		
Closed loop control	To all waypoints up to time fix waypoint	To time fix waypoint only
Wind compensation	Yes	Yes
Turn compensation	Yes	Not applicable
Speed commands	IAS	IAS
Time error display	Yes	Yes

3.2 EMULATED 4D RNAV CHARACTERISTICS

The Collins ANS-70A Automatic Navigation System was used as the basis for the time control system design. An operator's guide for this system can be found in ref 9. The system utilizes a general purpose computer and CRT control/display unit. As a result, software modifications were relatively straightforward. A limited production version of the 8564B computer was utilized for this program to provide the additional sensor input required for the ILS capture/tracking. Effectively, the only difference is in the aircraft system coupler (the input/output device). Software modifications to the ANS-70A software for emulating an air carrier

level 4D system were limited to adding a time control algorithm and the necessary control display capability. To include these features, automatic generation of holding patterns and inertial complementation of VOR/DME data were removed.

3.2.1 4D RNAV Control/Display Modifications

The flight progress page (PROG) of the ANS-70A system was modified to allow for insertion of the time fix and desired time of arrival data and display both the commanded IAS and the EARLY/LATE data. Data/label lines 5 (which normally display HDG CMD and REQ.V<) now display the following format (figure 3-7).

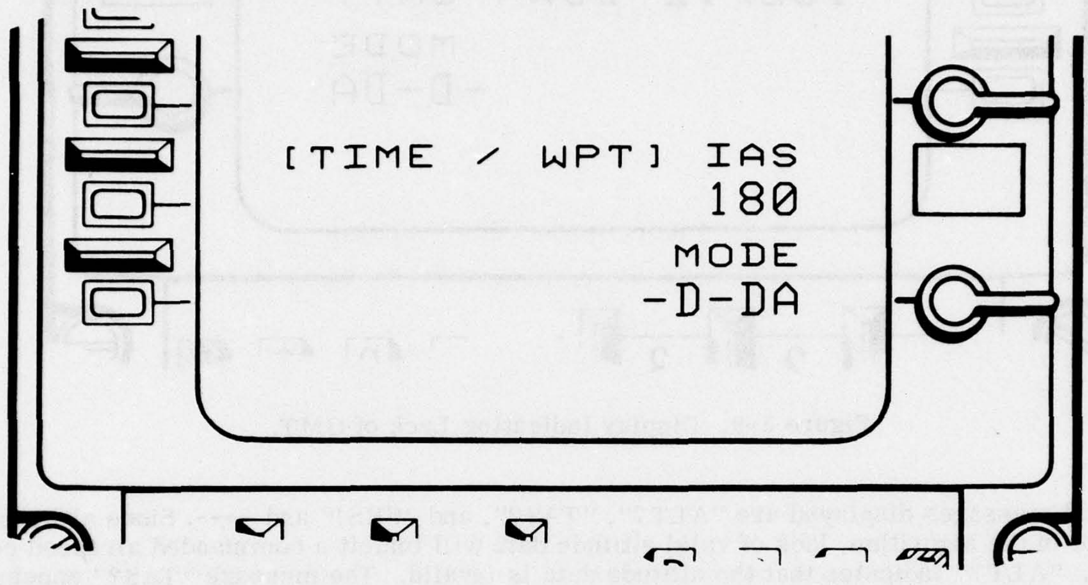


Figure 3-7. Entry Format for Time at a Waypoint and a Speed Command.

Under IAS, 180 represents the nominal airspeed over the leg as determined from the flight plan. Upon entry of a time and waypoint, the commanded airspeed (IAS) is displayed as shown (figure 3-8).

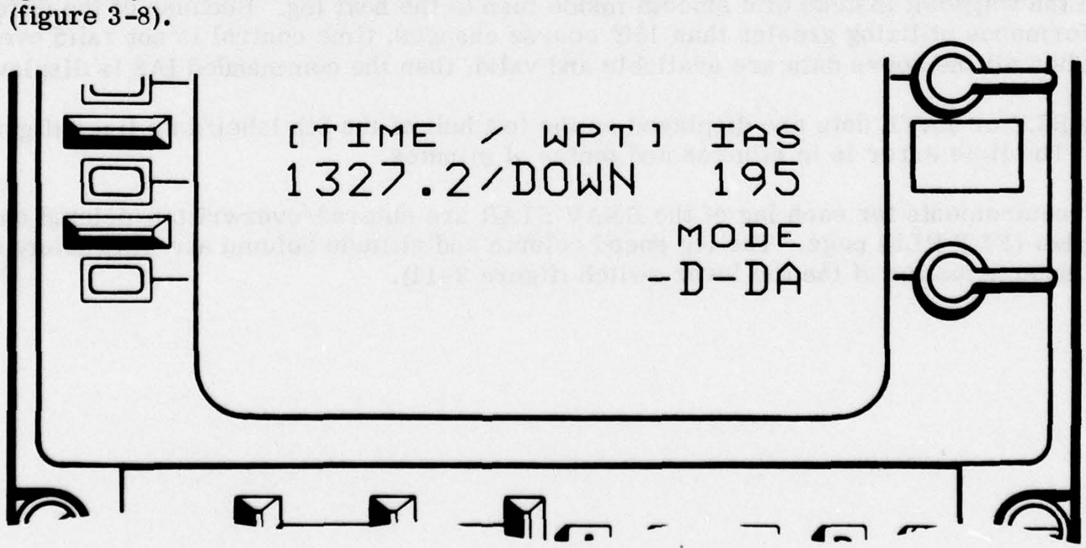


Figure 3-8. A Time/Waypoint Data and a Closed Loop Speed Command.

The calculations for determining IAS are in the algorithm descriptions (paragraph 3.2.2).

If GMT was not entered, or GMT base was lost due to power interrupt 2 seconds, "GMT?" appears in the IAS field, until such time that GMT is available (figure 3-9).

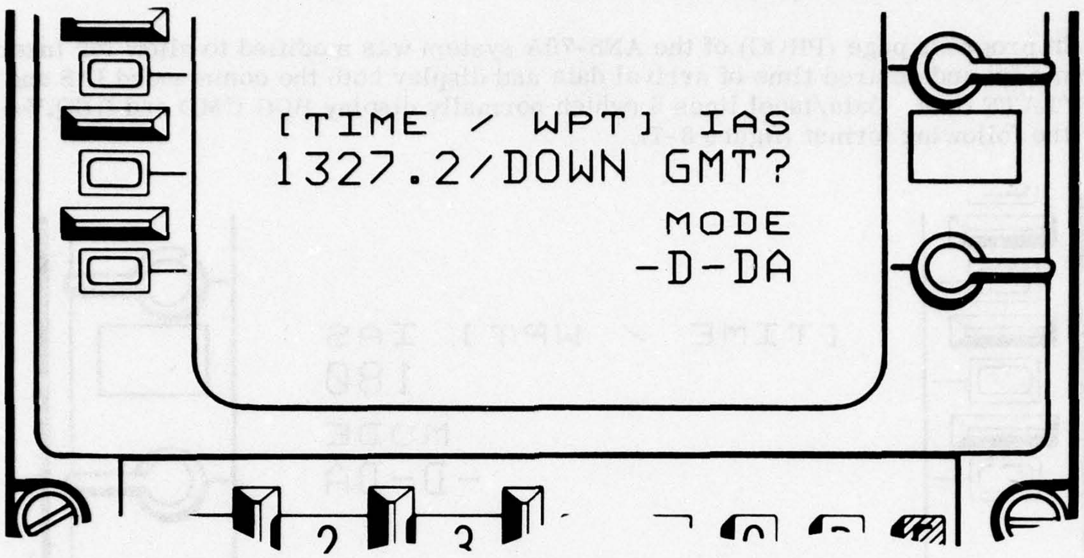


Figure 3-9. Display Indicating Lack of GMT.

Additional messages displayed are "ALT?", "TAS?", and "CRS!" and ----. Since altitude data is needed in the algorithm, lack of valid altitude data will inhibit a commanded airspeed computation. "ALT?" indicates that the altitude data is invalid. The message "TAS?" appears if no valid TAS is available. Four dashes (- - - -) are used to indicate lack of valid speed data. It usually implies that no speeds have been entered in the flight plan. Under this condition a nominal flight time cannot be set up and again a commanded airspeed cannot be computed. The message "CRS!" indicates a greater than 160° turn is called for in the flight plan to the time fix. The 3D system will then fly a relatively imprecise teardrop pattern beyond the waypoint instead of a smooth inside turn to the next leg. Because of the differences in performance utilizing greater than 160° course changes, time control is not valid over this leg. When all the above data are available and valid, then the commanded IAS is displayed.

The EARLY or LATE data are displayed on the left half of the 6th label/data lines (figure 3-10). The time error is in minutes and tenths of minutes.

Speed requirements for each leg of the RNAV STAR are entered/overwritten/deleted on the flight plan (FLT·PLN) page. The leg speed column and altitude column are alternately displayed upon actuation of the top lever switch (figure 3-11).

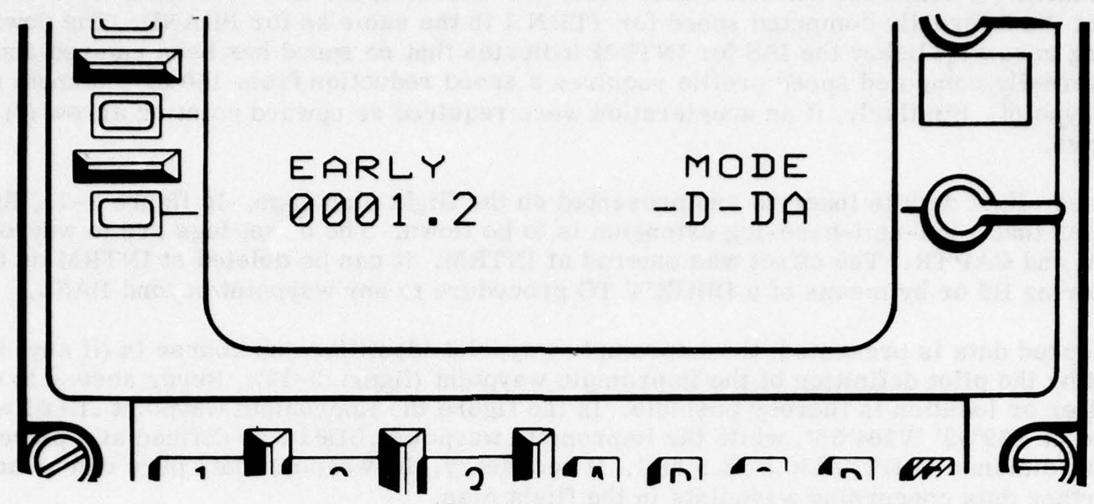


Figure 3-10. Display of EARLY/LATE Data.

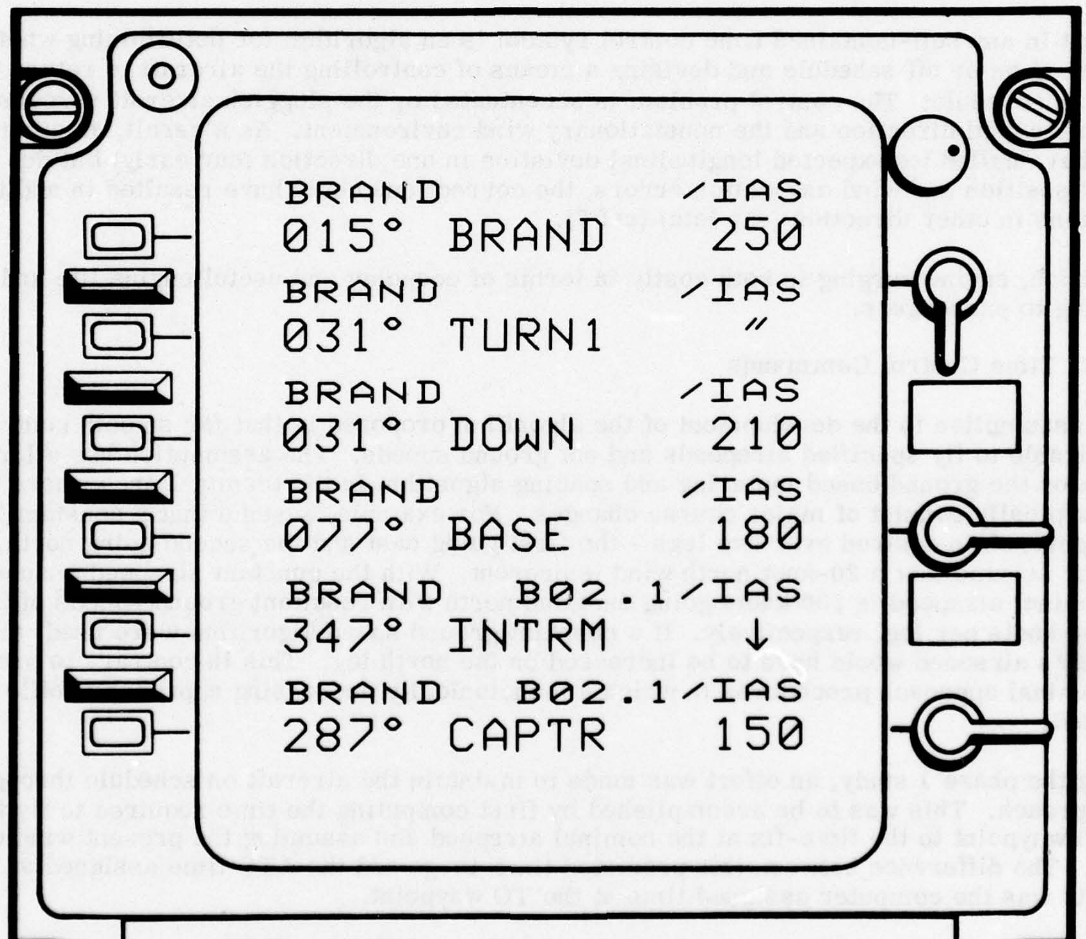


Figure 3-11. Speed Display of Flight Plan Page.

Ditto marks (") below the IAS for TURN 1 indicate that no speed has been entered for TURN 1 but that the internally computed speed for TURN 1 is the same as for BRAND. The downward pointing arrow (↓) below the IAS for INTRM indicates that no speed has been entered and that the internally computed speed profile requires a speed reduction from 180 to 150 knots through this waypoint. Similarly, if an acceleration were required an upward pointing arrow (↑) would be shown.

Any base offset data is inserted and presented on the flight plan page. In figure 3-11, BØ2.1 indicates that a 2.1-nmi-base-leg extension is to be flown. The offset legs are to waypoints INTRM and CAPTR. The offset was entered at INTRM. It can be deleted at INTRM or CAPTR by entering BØ or by means of a DIRECT TO procedure to any waypoint beyond BASE.

When speed data is presented, the impromptu waypoint identifier and course in (if any) is replaced by the pilot definition of the impromptu waypoint (figure 3-12). Ready access to either identifier or location is thereby possible. In the figure the impromptu waypoint .LLØ1 was defined at N39°39' W104°38', while the impromptu waypoint .BDØ1 was defined at a place/bearing/distance of DEN/150.5°/6.9 nmi. If necessary, the waypoint data page can be accessed for further data concerning waypoints in the flight plan.

3.2.2 Time Control Algorithm

Inherent in any self-contained time control system is an algorithm for determining whether an aircraft is on or off schedule and devising a means of controlling the aircraft to return to or maintain schedule. The control problem is accentuated by the sluggish aircraft response in the longitudinal direction and the nonstationary wind environment. As a result, an aircraft could have nulled its expected longitudinal deviation in one direction (say early) but due to typical position and wind estimation errors, the corrections could have resulted in additional deviations in other direction (say late) (ref 7).

In addition, engine surging is both costly in terms of economy and useful engine life and annoying to passengers.

3.2.2.1 Time Control Commands

A key assumption in the development of the algorithm proposed is that for smooth control it is desirable to fly specified airspeeds and not ground speeds. The assumption has a large impact on the ground based metering and spacing algorithm in the terminal area where flight plans typically consist of major course changes. For example, assume that a constant 200-knot approach is desired over two legs - the first going east and the second going north. Further assume that a 20-knot north wind is present. With the constant airspeed assumption, the nominal airspeed is 200 knots going east and north with resultant ground speeds of 200 and 180 knots per leg, respectively. If a constant ground speed algorithm were used, the aircraft's airspeed would have to be increased on the north leg. This is contrary to present day nominal approach procedures in which a monotonically decreasing approach profile is provided.

During the phase 1 study, an effort was made to maintain the aircraft on schedule throughout the approach. This was to be accomplished by first computing the time required to fly from the TO waypoint to the time-fix at the nominal airspeed and assuming the present wind condition. The difference between this predicted time-to-go and the ATC time assigned at the time fix was the computer assigned time at the TO waypoint.

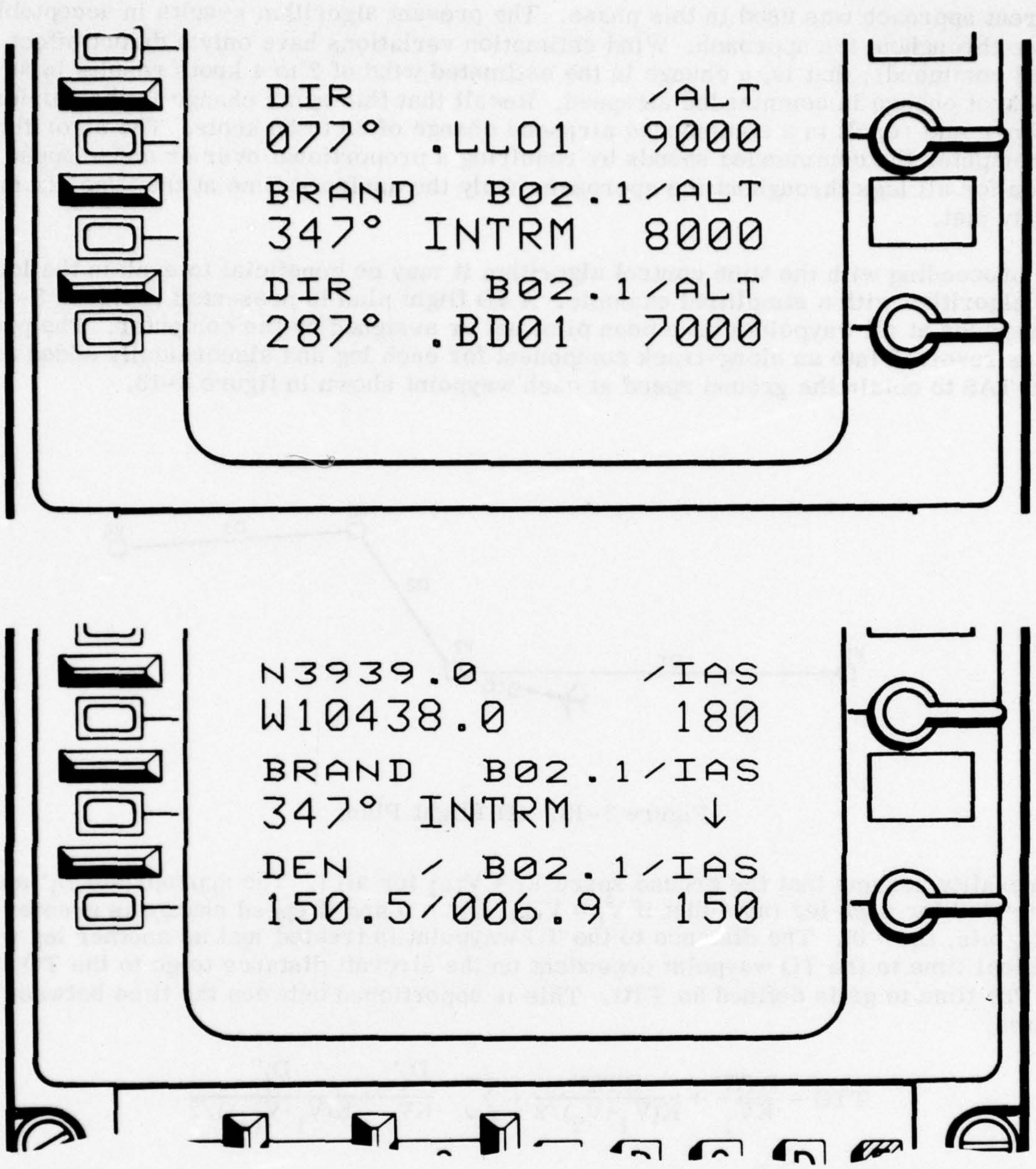


Figure 3-12. Display of Impromptu Waypoint Data Accessible Through Top Line Select Key.

Due to wind estimation errors, the algorithm functioned poorly through the early part of the approach. Wind estimation changes of 2 to 4 knots early in the approach would correspond to changes in predicted time to go of 1 to 2 minutes. Hence, the computer assigned time at the TO waypoint would change by 1 to 2 minutes. As the TO waypoint was approached, commanded speed variations of 25 to 50 knots resulted as the algorithm nulled the error at each TO waypoint. This requirement was *too* rigid, particularly far out in approach where the sensitivity to wind estimation errors was great.

A different approach was used in this phase. The present algorithm results in acceptable response throughout the approach. Wind estimation variations have only a direct effect on airspeed commands; that is, a change in the estimated wind of 2 to 4 knots results in at most a 2 to 4 knot change in commanded airspeed. Recall that this same change in the earlier algorithm could result in a commanded airspeed change of 25 to 50 knots. The algorithm in effect computes the commanded speeds by requiring a proportional over or under speed variation for all legs throughout the approach. Only the assigned time at the time-fix must be rigidly met.

Before proceeding with the time control algorithm it may be beneficial to explain the logic for the algorithm with a simplified example. A 4D flight plan is presented in figure 3-13. The airspeeds at all waypoints have been pilot set or assigned by the computer. The present wind was resolved into an along-track component for each leg and algebraically added to the desired TAS to obtain the ground speed at each waypoint shown in figure 3-13.

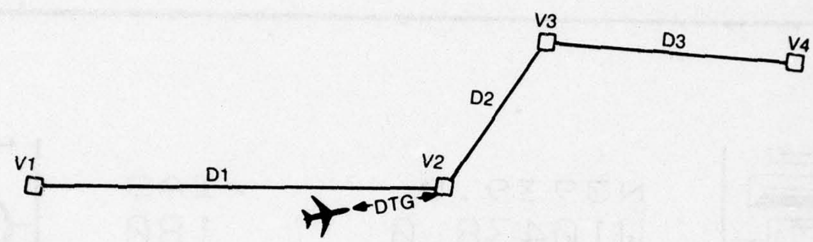


Figure 3-13. 4D Flight Plan.

For generality assume that the ground speed $V_i \neq V_{i+1}$ for all i. The appropriate D_i' and D_i'' are computed for each leg (note that if $V_i = V_{i+1}$, $D_i'' = 0$ and if speed change is greater than 40 knots/min, $D_i' = 0$). The distance to the TO waypoint is treated just as another leg with the nominal time to the TO waypoint dependent on the aircraft distance to go to the TO waypoint. The time to go is defined as TTG. This is apportioned between the time between legs as follows:

$$TTG = \frac{DTG'}{KV_1} + \frac{DTG''}{K(V_1+V_2)/2} + \sum \frac{D_i'}{KV_i} + \frac{D_i''}{K(V_i+V_{i+1})/2}$$

over all succeeding legs to time fix.

A constant of proportionality, K, has been introduced on all the velocity terms. With K set to 1, the TTG is just the nominal time along the flight path to the time fix, assuming that the nominal speed profile is flown. Note that the equation can be rewritten:

$$TTG = \frac{1}{K}\left(\frac{DTG'}{V_1} + \frac{DTG''}{(V_1+V_2)/2} + \sum \frac{D_i}{V_i} + \frac{D_i''}{(V_i+V_i+1)/2}\right)$$

$$= \frac{1}{K}(TTG_{NOM})$$

over all succeeding legs to time fix.

Thus if one sets the TTG equal to the time difference between the desired time of arrival at the time fix and GMT, the value of K will indicate the ratio of nominal time-to-go to commanded time-to-go. Let this same ratio be used to specify the ratio of the commanded ground speed over each leg to nominal ground speed. If this control strategy is used in setting commanded groundspeeds, the predicted time at the time fix is the commanded time at the time fix. The defining equation can be represented as follows:

$$\frac{TTG_{nom}}{TTG_{com}} = K = \frac{V^{GS}_{com}}{V^{GS}_{nom}}$$

This is the control strategy upon which the system is based. The system attempts to reduce the deviation in the aircraft's longitudinal position by proportionately modifying the speed over all succeeding legs to the time fix. It does not attempt to eliminate the time deviation at each waypoint. However, the deviation is monotonically reduced over the remaining distance to go.

As the flight proceeds and the wind estimate changes, the resultant change in commanded airspeed is directly proportional to the change in wind estimate. Navigation errors result in much smaller changes in commanded airspeed. Hence, the sensitivity of commanded airspeeds to system errors is much less than that experienced in references 1 and 3. In addition if necessary, a means of tighter tracking throughout the entire flight path is also possible with the same algorithm. This is explained in detail in paragraph 5.2.4.

The flow chart in figure 3-14 indicates the logic of the time control algorithm. The algorithm first monitors if sufficient navigation data is available for closed loop time control. Display of GMT? is removed by entering a GMT on the present position page. TAS? and ALT? are no longer displayed when the TAS computer and altimeter invalidities are removed. The IAS flag is set in the speed allocation module (figure 3-16). This logic block is passed when at least one speed is entered into the flight plan.

The assigned or preset IAS at each waypoint is converted to TAS by using the criterion that IAS decreases from 1 to 1-1/2 percent per thousand feet altitude. Present TAS and IAS are used to quantify the prevailing percentage. Following this, the nominal ground speed at each waypoint is computed by assuming a constant wind and algebraically adding the along-track component of wind for each leg to the TAS associated with the leg. The nominal IAS and ground speed of the aircraft at its present location and the nominal time-to-go to the TO waypoint are also computed.

If the pilot has not entered the desired time of arrival and the time fix waypoint, the nominal airspeed for the aircraft at its present position is displayed. If the data has been entered but a course change greater than 160° exists in the flight plan between the TO waypoint and the time fix, CRS! is displayed. Assuming all data is entered and a valid time control flight plan exists, the nominal time-to-go over each leg is then calculated and added to the time-to-go to the leg. The algorithm compensates for turns by assuming that a circular flight path will be flown at a constant bank limit. The time difference between the straight line path and the circular path is then subtracted from the nominal leg time. The process is continued until the nominal time to go is calculated.

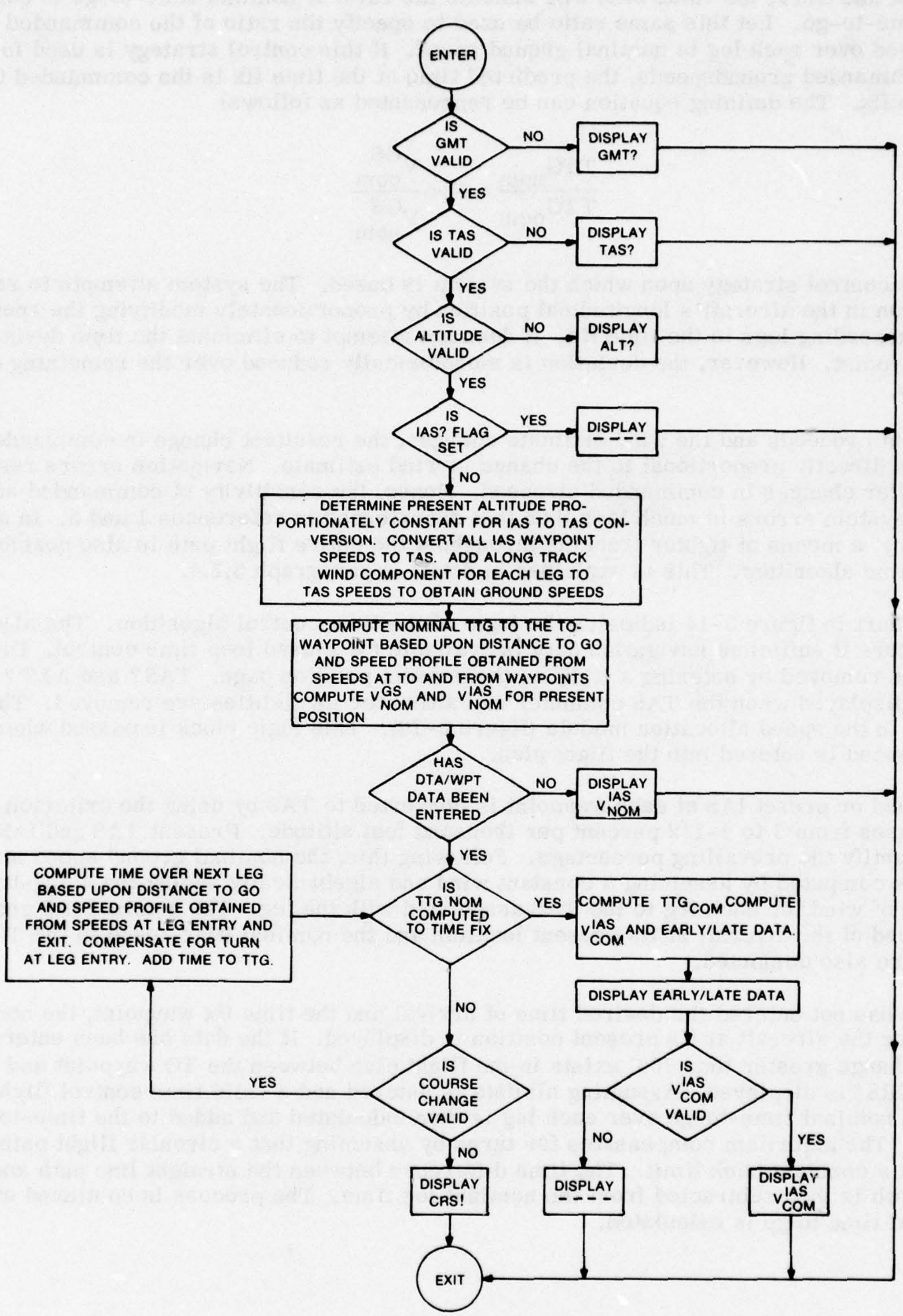


Figure 3-14. Commanded Airspeed Algorithm Flow Chart.

The commanded time-to-go is computed as the difference between present GMT and the desired time of arrival. Commanded ground speed is computed as defined earlier, followed by computations of commanded TAS (along-track wind algebraically subtracted from commanded ground speed) and then commanded IAS via the TAS to IAS conversion. The early/late display is computed similar to the commanded velocity. Namely, the predicted actual time-to-go is computed from the following relationship:

$$\frac{TTG_{act}}{TTG_{nom}} = \frac{V^{GS}_{nom}}{V^{GS}_{act}}$$

The difference between actual time-to-go and commanded time-to-go provides the early/late indication.

The system then checks if the IAS command is valid. For example, if the actual time-to-go is negative, the commanded speeds will come out negative. Under this condition, dashes are again displayed. If the commanded IAS is assumed valid, the computed value is displayed. This completes the description of 4D airspeed algorithm.

3.2.2.2 Nominal Speed Profile

During the phase 1 experiments, the speed profile was generated by assuming a linear speed profile between waypoints with different assigned speeds. Since it is a common practice to hold a speed and then slow to a new speed a set distance before a (reference) waypoint, additional waypoints had to be created at points where speed changes initiated or terminated. Two problems arose: the flight plan had to be enlarged to include speed control waypoints that were not lateral or vertical reference waypoints and navigation (distance, time to go) was referenced to the speed control point and not the succeeding reference waypoint.

It was, therefore, desirable to eliminate these speed control waypoints. The method used is explained in the following paragraphs. It is important to note that the method used or rate specified need not be as given in this program, but that some standard procedure be used to effect speed changes in the approach without requiring additional waypoints or much additional pilot data entry.

In the interest of minimizing data entry, it was assumed that all speed changes will be accomplished at the rate of 40 knots/minute just prior to the arrival of the speed control waypoint. If waypoints are in such close proximity and the speed change is of such great magnitude that a greater than 40-knot/minute change is required, then this value is used in computing the speed profile (figure 3-15). If not, the airspeed is assumed to be held constant until the point at which the 40-knot/minute acceleration rate is initiated. The 40-knot/minute rate is within

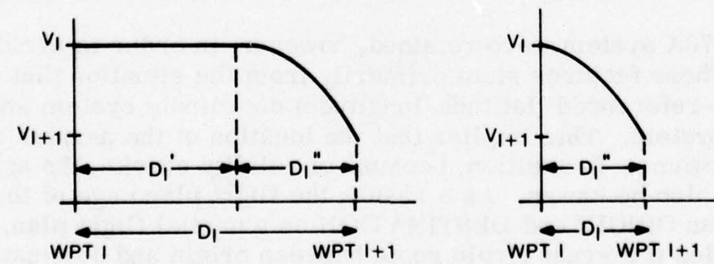


Figure 3-15. Speed Profiles.

the acceleration/deceleration capability of most aircraft. The use of the preprogrammed rate minimizes the number of speed entries and typically does not require additional waypoints other than the 2D or 3D waypoints used for lateral and vertical guidance. In addition, the number of pilot inserted speeds is typically limited to the number of different nominal airspeeds specified per approach.

3.2.2.3 Speed Assignments At Nonspeed Control Waypoints

The speed computation involves only those waypoints at which a speed has not been set by the pilot. These waypoints are assigned a speed based upon the speeds at surrounding speed control waypoints and the distance between these waypoints, hence, the distinction between set speeds and assigned speeds. Set speeds are set by pilot entry, define speed control waypoints, and are not altered by the algorithm. Assigned speeds are assigned by the algorithm at nonspeed control waypoints and may change automatically at each iteration. The only exception to this is the speed associated with the FROM waypoint. The FROM waypoint is always given a set speed either by pilot entry before waypoint passage or by computer upon waypoint passage.

The time control data is computed every 10 seconds or whenever the flight plan is altered. This includes altering 2D or 3D waypoint data as well as speed data. In addition, the time control data is recomputed at waypoint passage.

A flow chart of the speed assignment algorithm is shown in figure 3-16. The routine first searches for the speed associated with the FROM event. Upon initial entry none may have been assigned. If not, speed at the FROM waypoint is then set to the initial speed entered in the flight plan. If no speeds have been entered into the flight plan, a flag is set and no time control information will be displayed.

Following assignment of a speed at a waypoint, search is made for the next speed control waypoint. If none exists, a constant speed profile is assumed for the remainder of the flight. If one exists and a speed change is required, then the distance required to effect the speed change, D'', is calculated (figure 3-15). Waypoints a distance greater than D'' from the next speed control waypoint are then assigned speeds of the prior speed control waypoint. Waypoints within D'' are assigned speeds based on the necessary acceleration rate.

This process is continued until all waypoints in the flight plan have a speed associated with them.

3.3 2D/TIME CONTROL CHARACTERISTICS

The 2D plus time control system utilizes the same ANS-70A hardware as the 4D time control system. All system changes were controlled by software. Commonality of equipment, including wiring, was maintained to allow greater flexibility in testing system concepts.

Certain features of the ANS-70A system were retained, however, in order to avoid a massive overwrite of the software. These features stem primarily from the situation that the ANS-70A system navigates in an earth-referenced (latitude/longitude) coordinate system and not a station-oriented coordinate system. This implies that the location of the navaids must be known to the navigation algorithms. In addition, because of validity checks, the approximate position of the aircraft must also be known. As a result, the flight plan page of the ANS-70A system is retained to set up an ORIGIN and DESTINATION as a partial flight plan. Intermediate waypoints can be added if a great circle route between origin and destination is not flown. Following a PUSH TO ACCESS TAPE and the DATA SEARCH, location of all navaids (up to a limit) along the flight plan is stored in the computer. Similarly the present position

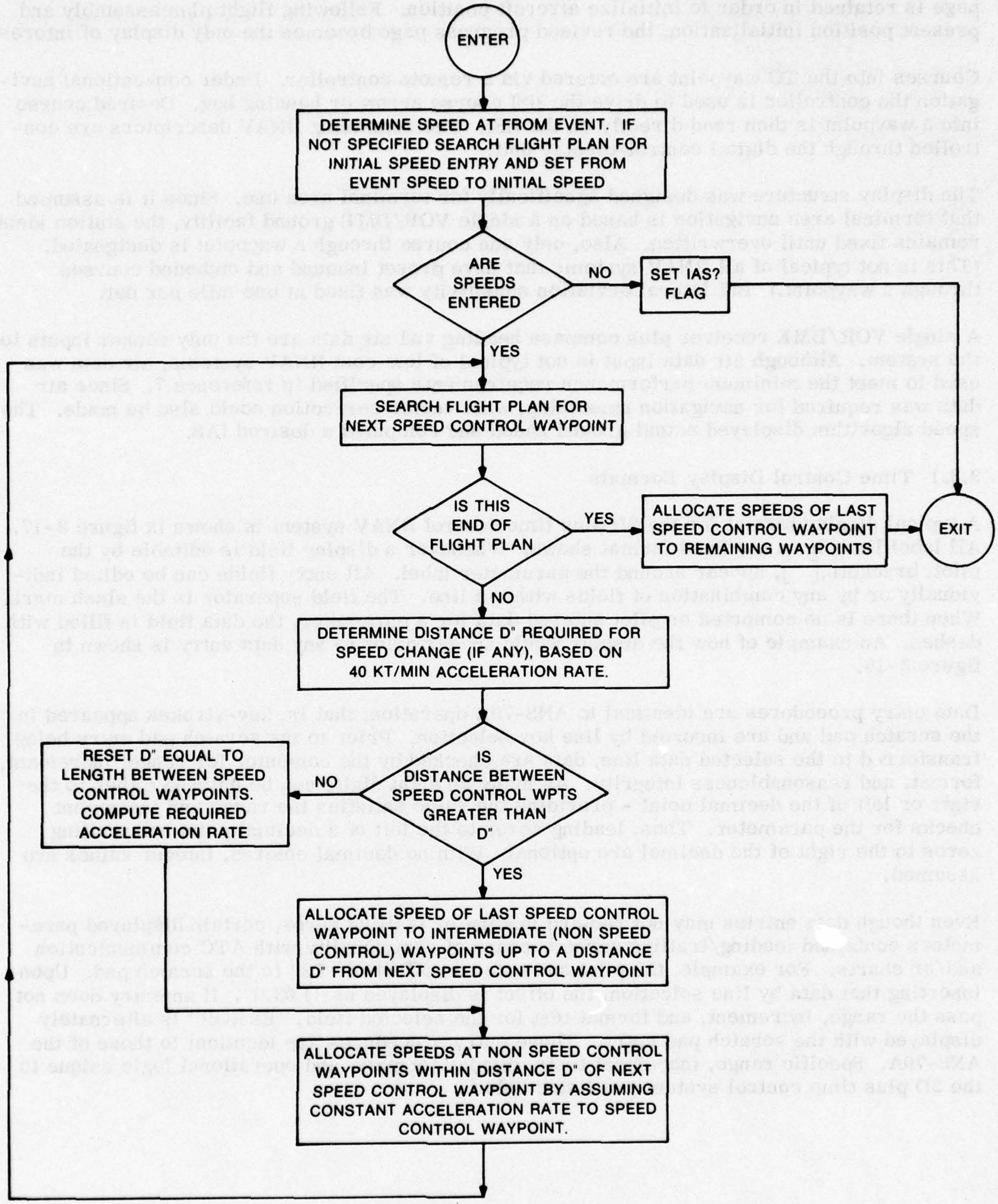


Figure 3-16. Speed Allocation Algorithm Flow Chart.

page is retained in order to initialize aircraft position. Following flight plan assembly and present position initialization, the revised progress page becomes the only display of interest.

Courses into the TO waypoint are entered via a remote controller. Under conventional navigation the controller is used to drive the HSI course arrow or heading bug. Desired course into a waypoint is then read directly on the HSI. The remaining RNAV descriptors are controlled through the digital control/display unit.

The display structure was designed specifically for terminal area use. Since it is assumed that terminal area navigation is based on a single VOR/DME ground facility, the station ident remains fixed until overwritten. Also, only one course through a waypoint is designated. (This is not typical of all RNAV systems that have preset inbound and outbound courses through a waypoint.) HSI lateral deviation sensitivity was fixed at one mile per dot.

A single VOR/DME receiver plus compass heading and air data are the only sensor inputs to the system. Although air data input is not typical of low-cost RNAV systems, air data was used to meet the minimum performance requirements specified in reference 7. Since air data was required for navigation smoothing, wind vector correction could also be made. The speed algorithm displayed actual ground speed and computed a desired IAS.

3.3.1 Time Control Display Formats

A typical display format for the 2D plus time control RNAV system is shown in figure 3-17. All label lines have the fixed format shown. Whenever a display field is editable by the pilot, brackets,[ ], appear around the parameter label. All entry fields can be edited individually or by any combination of fields within a line. The field separator is the slash mark. When there is no computed or pilot entered data for a parameter, the data field is filled with dashes. An example of how the display would appear prior to any data entry is shown in figure 3-18.

Data entry procedures are identical to ANS-70A operation; that is, key-strokes appeared in the scratch pad and are inserted by line key selection. Prior to the scratch pad entry being transferred to the selected data line, data are checked by the computer for range, increment, format, and reasonableness integrity. As many as eight digits can be entered either to the right or left of the decimal point - providing the value satisfies the range and increment checks for the parameter. Thus, leading zeros to the left of a decimal point and trailing zeros to the right of the decimal are optional. With no decimal entered, integer values are assumed.

Even though data entries may not require leading or trailing zeros, certain displayed parameters contained leading/trailing zeros because of commonality with ATC communication and/or charts. For example, the pilot can enter an offset of "L3" to the scratch pad. Upon inserting that data by line selection, the offset is displayed as "LØ3.0". If an entry does not pass the range, increment, and format test for the selected field, "ERROR" is alternately displayed with the scratch pad entry. These entry procedures are identical to those of the ANS-70A. Specific range, increment tests, display formats, and operational logic unique to the 2D plus time control system are listed below.

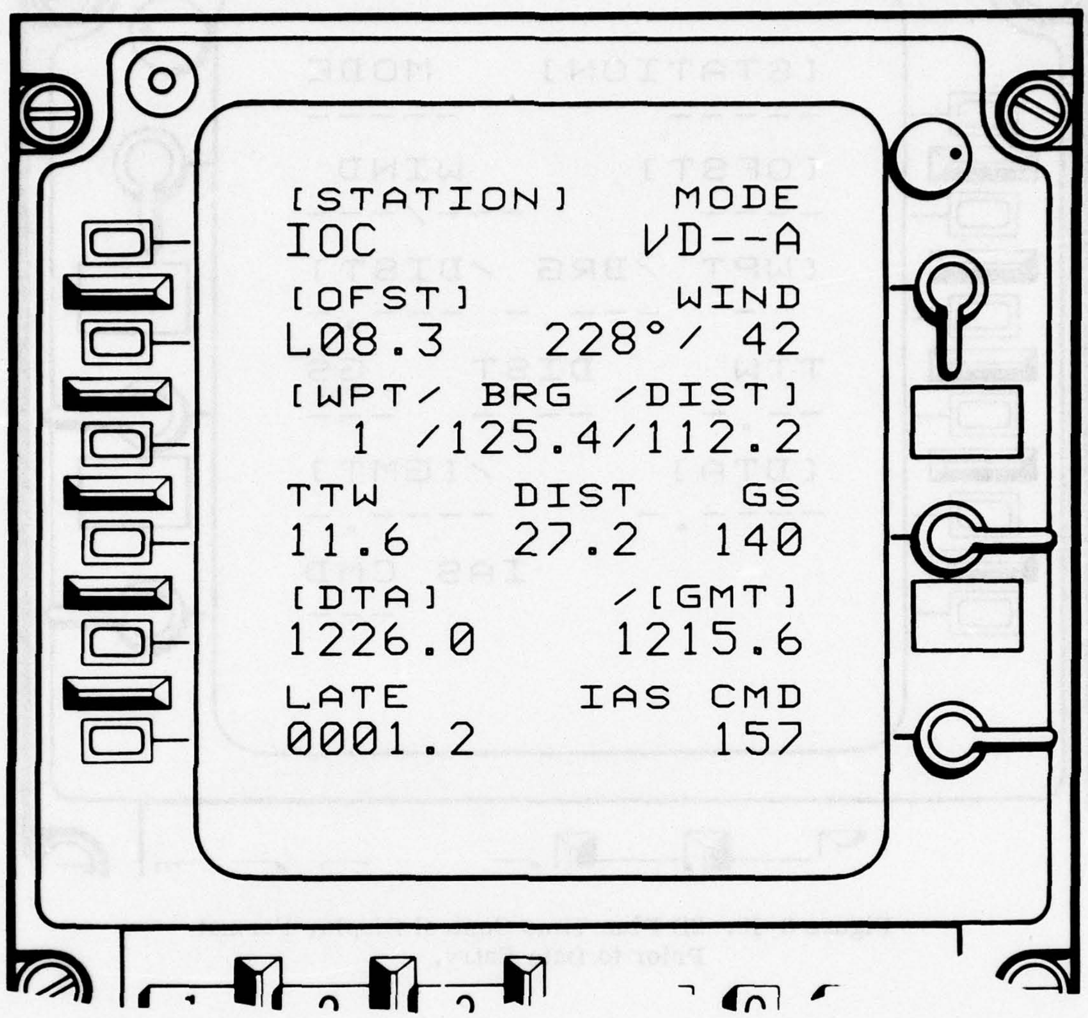


Figure 3-17. Typical Display for the 2D Plus Time Control System.

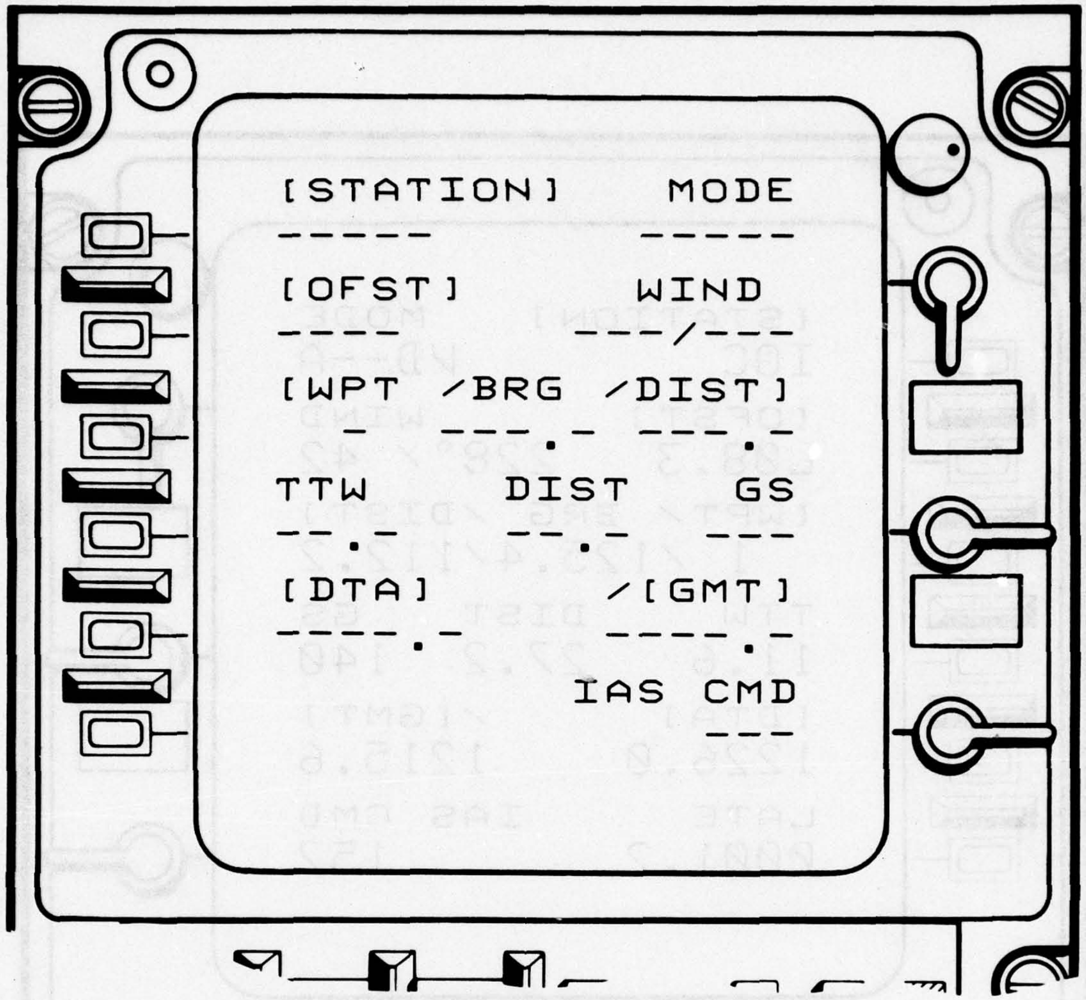


Figure 3-18. 2D Plus Time Control Display Format
Prior to Data Entry.

3.3.1.1 VOR/DME Station [STATION]

Entry of a navigation station identifier tunes the receiver to that station. While the use of station ident instead of station frequencies is not representative of most 2D RNAV systems, retaining this ANS-70A feature was considered necessary. In addition, digital entry of IDENT in contrast to digital entry of frequency is felt to be of similar workload and complexity. Loss of navaid signal from the receiver is displayed by the mode indication and by dropping the NAV flag on the HSI. The "loss of signal" is reset by receiving valid inputs from the receiver. A station is changed only by writing with a new station ident.

3.3.1.2 Navigation Mode [MODE]

Navigation mode is the system operating mode. The primary mode consisting of VOR, DME, and air data/heading is displayed as V, D, and A, respectively. Loss of any valid signal is indicated by displaying "-" (minus sign) for that signal. When downgrading to a nonradio mode

occurs (loss of VOR or DME) the display blinks. Blinking is canceled by typing "-" (minus sign) on the scratch pad and pressing the upper left-hand line-select key.

3.3.1.3 Parallel Offset [OFST]

Offset value must be preceded by a "L" or "R". Cancelation of the offset is by left or right zero (LØ or RØ) entry. The offset remains in effect until canceled, regardless of changes in course or waypoints.

3.3.1.4 Wind [WIND]

Wind direction and velocity are displayed when air data is valid. When air data is invalid, dashes are displayed. Direction is displayed as bearing from. No edits to the wind data are permitted.

3.3.1.5 Waypoint/Bearing/Distance [WPT/BRG/DIST]

Entry of a "0" through "9" is permitted for identifying waypoint bearing/distance. Entry of a minus sets the waypoint bearing and distance to zero (the waypoint is then coincident with the station). Navigation is then to the station. Bearing and distance information is stored with the respective ident (0 through 9) so that entry of 0 displays the bearing/distance information for waypoint 0; entry of a 1 display the bearing/distance associated with waypoint 1 etc. If a waypoint definition is incomplete; that is, if dashes are displayed for any of the data fields, "ERROR" is annunciated when the USE function is attempted. When displaying a waypoint definition that is not in use, the waypoint definition line blinks. Keying the PROG key will present the waypoint in use.

3.3.1.6 Time-To-Waypoint [TTW]

No edit functions are allowed. Time-to-waypoint is the estimated time to reach the waypoint in use (or the VOR if no waypoint/bearing/distance has been specified) based upon present ground speed and distance. If the time is greater than 99.9 minutes to the waypoint, display is 99.9.

3.3.1.7 Distance [DIST]

No edit functions are allowed. The distance is to the waypoint in use. Display range is from 0 to 999.9 nmi in 0.1-nmi increments.

3.3.1.8 Ground Speed [GS]

The ground speed is the present computed ground speed in knots. No edit functions are allowed.

3.3.1.9 Desired Time of Arrival [DTA]

Desired time of arrival is the time (GMT) at which the aircraft is supposed to pass the waypoint in use according to pilot entry. It determines the IAS command along the path to the TO waypoint. DTA can be edited by overwriting or deleted by a minus entry. DTA automatically changes to dashes when a new waypoint is selected for use.

3.3.1.10 GMT

GMT must be entered for the closed-loop time control simulation. A power interrupt of more than two seconds results in displaying dashes under the GMT label. GMT may be overwritten with a new time. The GMT entry is preceded by a slash mark.

3.3.1.11 IAS Command [IAS CMD]

The IAS command is only displayed when DTA and GMT are displayed, and when the NAV flag bit is valid. No edits to the IAS CMD field are allowed. Display range is from 000 to 400 in 1-knot increments.

3.3.1.12 Early or Late Indication [EARLY or LATE]

The early or late indication is provided wherever DTA has been entered and the TTW and GMT data are valid.

3.3.1.13 USE Key

A command key labeled "USE" is utilized for selecting the active or TO waypoint (figure 3-19). Operation of this key is unique to the 2D plus time control system. Activation of this key causes the waypoint defined in the waypoint/bearing/distance line to become the active waypoint for navigation. If an incomplete waypoint definition exists when the waypoint line is selected, the message "ERROR" is blinked. The message is cleared via the CLR key.

3.3.2 Time Control Algorithm

The time control algorithm for this system is simplified greatly as the time fix is the TO waypoint. EARLY/LATE data can be obtained by adding the TTW to GMT and subtracting this quantity from DTA with positive implying early.

The commanded IAS is found as follows. The DTW is divided by the difference between GMT and DTA to obtain the desired ground speed. The along-track component of the wind is algebraically subtracted from this to obtain the commanded TAS. A TAS to IAS conversion is then performed, resulting in the commanded IAS.

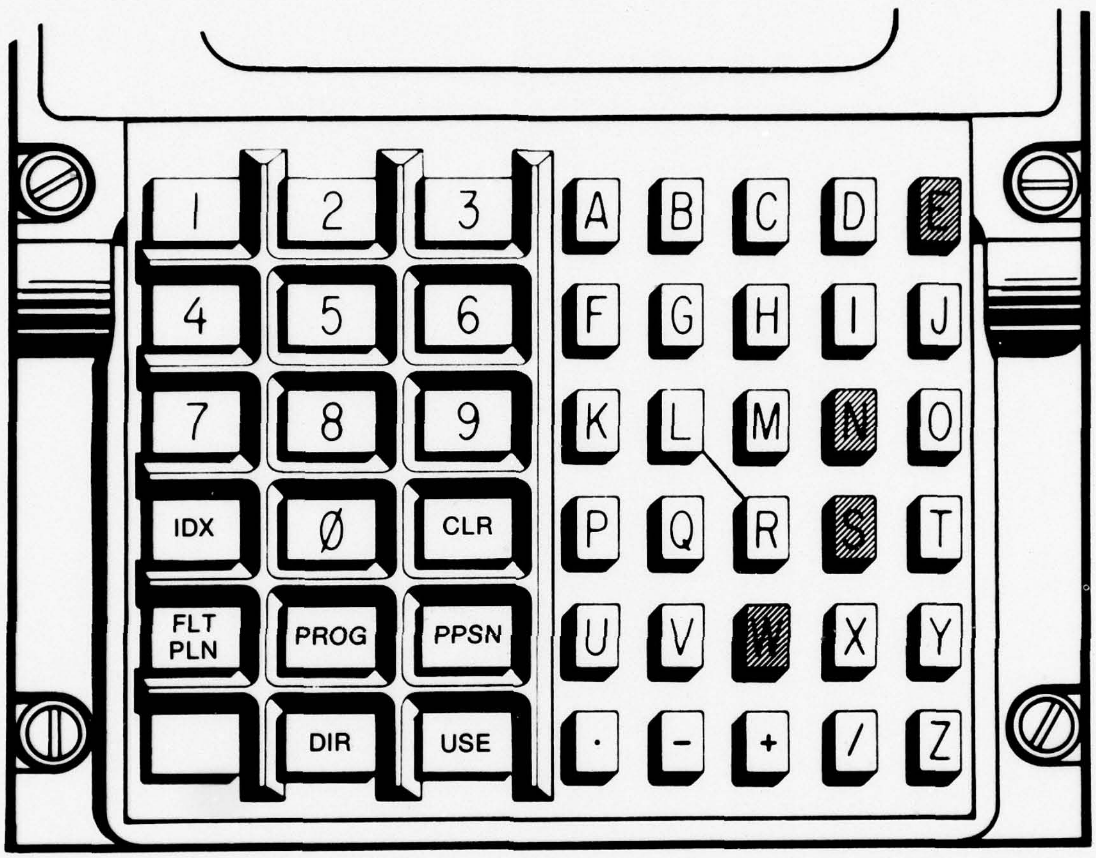


Figure 3-19. Modified Keyboard for the 2D Plus Time Control System.

4.1 INTRODUCTION

Area navigation in the terminal area has for the most part been limited to nonprecision approach guidance. Transition from VOR/DME based RNAV guidance to ILS guidance is usually initiated far enough distant from the localizer so that localizer capture is accomplished under conventional navigation techniques. Under autopilot control, with the autopilot armed for ILS capture, localizer capture is made via a heading hold, while glideslope capture is made via an altitude hold intercept. Significant crew workload is involved in tuning the radios and switching autopilot modes and navigation inputs. This activity takes place at the start of the most critical flight phase.

Because most aircraft utilize dual VOR/LOC receivers, tuning to an LOC frequency results in loss of VOR/DME for area navigation. Hence, unless dual equipments are carried with only one set tuned to the localizer, area navigation will be based upon dead reckoning with no VOR/DME updates. The degradation in accuracy would severely limit the attractiveness of closed loop time control during final approach.

Even from 3D navigation considerations the method of approach is deficient. Autopilot controlled heading hold localizer captures are limited by the narrowness of the localizer beam. Close in captures must be made at shallow capture angles unless aided by ATC vector communications. Yet the area navigation system could provide similar guidance if it were receiving navaid updates. If the transition to localizer guidance would not require any mode switching, pilot workload should be decreased. Finally, since the area navigation system is providing navigation, normal RNAV outputs can be used to improve capture/tracking performance. Improved performance on the beam would be provided due to linearization of the angular data.

For these reasons an RNAV aided/controlled ILS capture/tracking capability was designed for the 4D system. The system requires no mode switching external to the RNAV control/display unit. All mode logic and discrete validities are monitored and controlled internal to the RNAV system. The system concept is explained in greater detail below.

Glideslope capture is initiated after localizer capture. Capability to capture glideslope from above and below was included in the basic design.

The design was optimized for a Gulfstream G-1 aircraft with a Sperry SP-40C autopilot. RNAV longitudinal and lateral axis models of the autopilot were developed from data taken from field tests (figures 4-1 and 4-2). The models are for the altitude hold and heading select ports of the autopilot to which the 4D system will couple. The autopilot channels are optimized for cruise performance assuming certain noisy data. Under ILS control more accurate data is available and tighter performance is required. As a result, the lags in the autopilot resulting from smoothing the data were compensated for in the ILS control algorithms. Gains were also adjusted to ensure Cat II performance from the non-ILS autopilot ports.

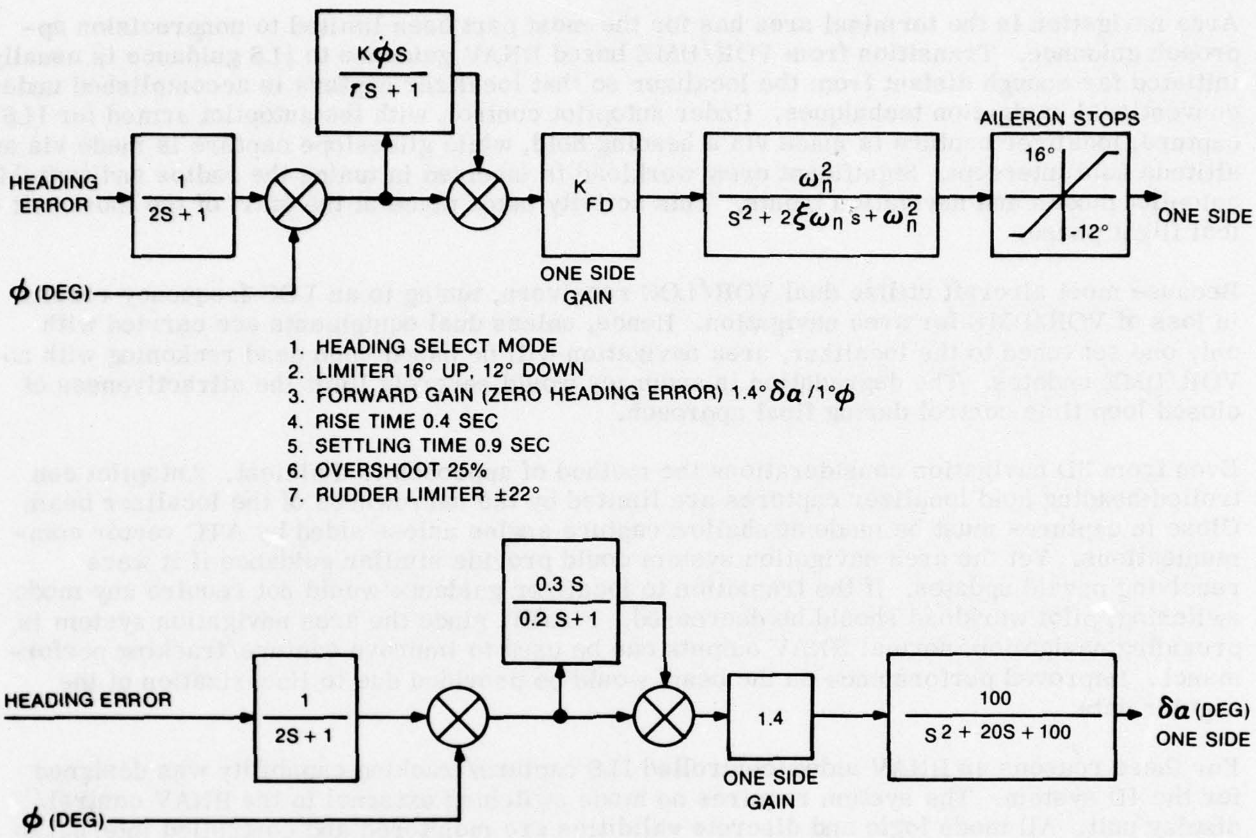
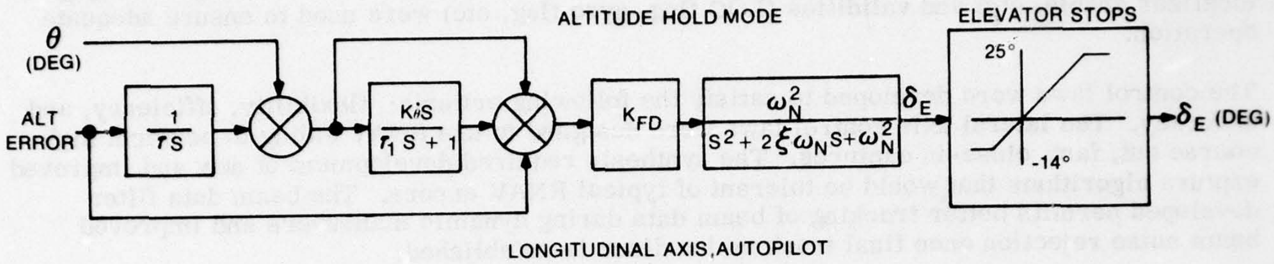


Figure 4-1. Lateral Axis Autopilot Linear Model.



KEY DATA PARAMETERS: (ZERO ALT ERROR, 1.4° PITCH)

1. LIMITER 25° UP, 14° DOWN
2. TIME TO PEAK 0.42 SEC.
3. OVERSHOOT 30%
4. SETTLING TIME 0.92 SEC
5. FORWARD GAIN 4 DEG δ_E / DEG θ
6. FORWARD GAIN (ZERO PITCH, 200 MV ALT ERROR) 1.25° θ_{CMD}/200 MV
7. INTEGRATION RATE 1.5° δ_E/ SEC.

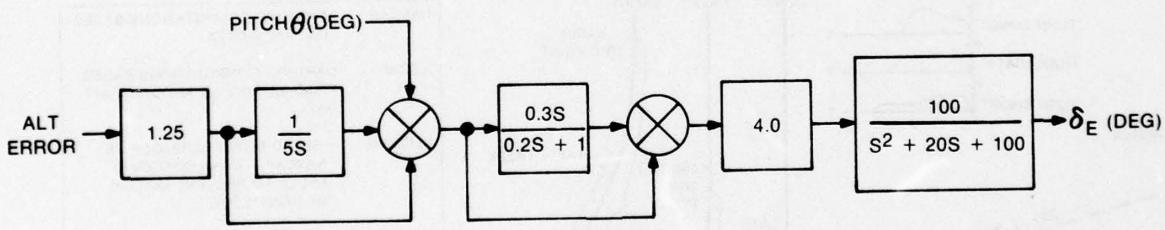


Figure 4-2. Longitudinal Axis Autopilot Linear Model.

4.2 ILS CONTROL LAW DEVELOPMENT

4.2.1 Localizer Capture/Track Design

The capture and track mode design was a logical extension of Collins past work with ILS computers. Based upon this experience it was known that some form of acceleration data would be needed for Cat II type localizer tracking particularly under wind shear conditions. A roll gyro input was considered adequate and typically available in contrast to inertial inputs or even body mounted accelerometers. This was the only additional sensor required over that used in the basic 4D system. Of course other discretes (such as autopilot engaged, localizer enable, etc) and validities (LOC flag, gyro flag, etc) were used to ensure adequate operation.

The control laws were developed to satisfy the following criteria: flexibility, efficiency, and accuracy. The lateral axis control laws were designed to use RNAV aiding to perform high course cut, fast, close-in captures. The synthesis required development of new and improved capture algorithms that would be tolerant of typical RNAV errors. The beam data filter developed permits better tracking of beam data during dynamic maneuvers and improved beam noise rejection once final track on localizer is established.

Figure 4-3 illustrates the various localizer capture modes. For 90° capture beyond 13 nmi, turn initiation does not depend on RNAV crosstrack estimates. Close-in captures require area navigation aiding. The area navigation system provides an estimate of crosstrack distance to localizer and along-track distance to touchdown. Based upon this, a trip point is computed as well as a predicted track angle error at localizer beam edge. If the RNAV

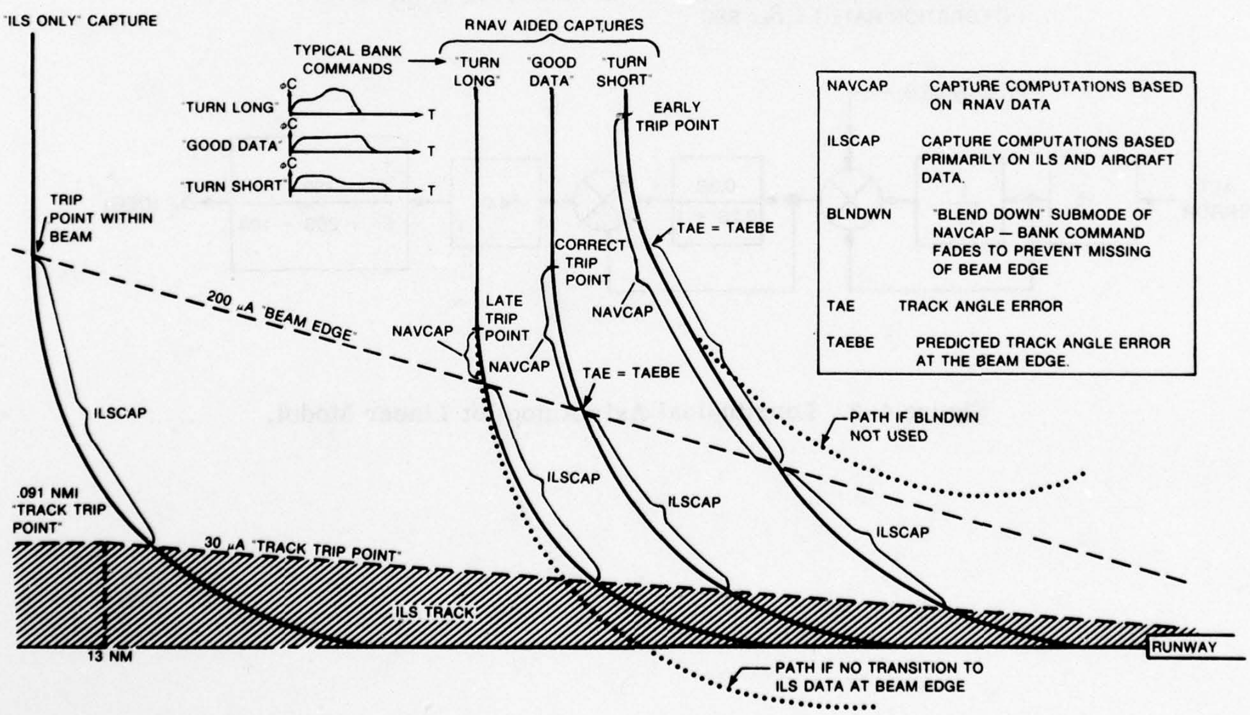


Figure 4-3. Area Navigation Aided Localizer Capture.

errors result in a late turn, sufficient controllability remains to capture the localizer without overshoot for crosstrack errors of less than 0.5 nmi. If the RNAV errors result in an early turn, the beam edge will not be sensed when the track angle is equal to its predicted value at beam edge and a blend-down procedure fades the bank so that the track angle error is never less than 7°. This prevents the RNAV errors from paralleling the localizer beam or even turning from it. The detailed equations are given below.

4.2.1.1 Blend-Down Algorithm

The need for a blend-down algorithm arises in the "turn-short" case. There are two aspects of the blend-down problem; when should the blend-down be initiated, and how should the blend-down be programmed? The first of these questions requires addressing the problem of "when has the system turned far enough?" The system will execute an approximately circular turn onto final course if the bank command (BNK.CMD) obeys the relationship.

$$BNK.CMD = -\tan^{-1} \frac{V_g^2 * (1 - COS(TAE))}{g*CTD} \tag{4-1}$$

where V_g is ground speed, TAE is track angle error or angle of ground velocity vector relative to the runway center line; CTD is crosstrack distance to localizer center line; and g is gravitational constant (32.17 ft/s^2), and consistent units are assumed. Equation 4-1 holds through the entire capture maneuver; and if all assumptions are satisfied, TAE and CTD change in such a way that BNK.CMD remains constant, assuming no wind. If there is a wind, the bank must change during the capture in order to maintain a circular track over the ground.

In particular, for a capture initiated outside the beam on RNAV data and neglecting wind for the moment, equation 4-3 should hold at the instant of beam intercept. Now at beam intercept, knowledge of range and localizer deviation (LOC.DEV) permits computation of crosstrack distance at the beam edge (CTDBE). Further, since V_g and BNK.CMD are known, track angle error at the beam edge (TAEBE) can be computed by solving equation 4-1 for TAE as

$$TAEBE = COS^{-1}\ 1. - \frac{g*\tan(-BNK.CMD)*CTDBE}{V_g^2} \tag{4-2}$$

where CTDBE = range * sin (LOC.DEV) with appropriate units used. If wind is present, equation 4-2 will still hold at any particular instant in the turn.

Simulation results indicated it was best to compute TAEBE once only at capture initiation and accept any resulting anomalies due to wind. Equation 4-2 is basically only used to define the trip point for transition to the blend-down submode. That is, one computes TAEBE at the initiation of capture and as the capture proceeds, he continually tests TAE against TAEBE. If the condition TAE equals TAEBE occurs prior to encounter of the beam edge, the system is presumably turning too fast and fading of the bank command should begin. If beam encounter occurs prior to TAE equals TAEBE, then the system should fade immediately to bank command based on beam data.

The second aspect of the blend-down problem is the question of how to fade the bank. Assuming an exponential fade on bank command, it can be shown that the time constant of the fade can be computed so that for a fade beginning at the point TAE equals TAEBE, the system will never turn further than to TAE equals k*TAEBE where 0<k<1. In particular, under no conditions will the system turn parallel to the beam. The bank command is faded exponentially from its initial value with a time constant (τ) computed as shown in equation 4-3.

$$\tau = \frac{Uo\ (k * TAEBE)}{g\phi(to)} \qquad (4\text{-}3)$$

where ϕ(to) is the bank angle at the initiation of the fade and Uo is airspeed.

4.2.1.2 Capture Trip Point

The basic requirement for capture trip point is that it be such that reasonable banks are used in capture and reasonable overshoots occur under all conditions. Generally bank command is restricted to less than 30° in magnitude in transport aircraft and it is highly desirable to keep overshoots less than 30 μA ($\approx$0.4°) of localizer deviation. Other factors also enter. For example, if no RNAV system is available, clearly the trip point must be within the beam resulting in geometry limits for certain close-in captures. Pilots often have very definite opinions about how the bank should behave under given conditions. The conditions above imply that the desired form of the capture bank command might be a feasible basis for computing the capture trip point. If one assumes a circular capture (that is, constant bank), it is interesting to solve equation 4-1 for CTD to illustrate the CTD required to execute a circular capture as a function of Vg, TAE, and BNK.CMD.

$$CTD = \frac{Vg^2 (1 - COS\ (TAE))}{g\ tan\ (BNK.CMD)} \qquad (4\text{-}4)$$

Equation 4-4 illustrates the generally applicable point that capture trip point expressed in CTD terms is a function of ground speed, TAE, and bank command to be used in the capture. Since it appeared feasible to specify a desired constant bank during capture, the approach decided on in this study was to specify the capture bank (CAP.BNK) and then use equation 4-4 to determine the trip point. However, the bank rate command limit is a significant factor and the trip point should be adjusted to account for its effect. Further, it was felt that the capture bank should be a function of TAE; that is, at high angle course cuts, more bank should be used than for lower angle course cuts. Further, to prevent very small bank captures, the restriction was added that capture bank be greater than 5° in all cases.

Tolerance to RNAV position and velocity errors must be considered in determining MAX.CAP.BNK, the maximum bank to be used in capture. In the event of a "turn long" case, the required "room to increase" on bank once the beam is encountered is a function of range. To see this, consider captures beginning at the same CTD and course cut but at varying range (RNAV data is used until beam intercept). Intuitively, at longer ranges more beam width in feet is available after beam intercept to correct the problem or conversely less time is spent using an erroneous command.

Making the maximum capture bank (MAX.CAP.BNK) sufficiently large at longer ranges will force the capture to be within the beam in those cases (equation 4-4). This is desirable since RNAV aiding should be used only when necessary. It was decided to make MAX.CAP.BNK = 25° at longer ranges and to decrease the value at shorter ranges. Further, it can be shown that for a 90° intercept at 200 fps, MAX.CAP.BNK = 25° implies RNAV aided captures at ranges shorter than 13-nmi range; hence, this seems a reasonable point to start programming MAX.CAP.BNK down. Numerical examples and simulation results indicated that provision for about 15° possible increase in bank during capture at 5 nmi seemed advisable.

Collecting the above discussion, the trip point computer is performed as follows:

$$\text{CTD trip point} = \frac{Vg^2(1-\text{COS(TAE)})}{g\ \tan(\text{CAP.BNK})} + \text{CTD.ADJ} \tag{4-5}$$

where

$$\text{CTD.ADJ} = \frac{\text{CAP.BNK}}{\text{RCL}} * Vg\ \sin(\text{TAE})$$

$$\text{CAP.BNK} = \begin{cases} -\text{MAX.CAP.BNK} * \dfrac{\text{TAE}}{90} \ldots & \text{if magnitude of result is} \geq 5° \\ -5 * \text{SIGN(TAE)} \ldots & \text{otherwise} \end{cases}$$

$$\text{MAX.CAP.BNK} = (8.0 + \frac{17}{13} * \text{RNGLOC}) \leq 25°$$

RCL is the rate command limit and

RNGLOC is range to localizer in nmi and the units on MAX.CAP.BNK are degrees.

CTD trip point as a function of range and course cut is shown in figure 4-4 for a speed of 200 fps. Superimposed on this plot are lines for 200 μA (ILS CAP "beam edge") localizer deviation and "track trip." These are significant boundaries, for they delineate NAVCAP, ILSCAP, and track regions respectively.*

The transition from capture to track normally occurs when

$$\text{LOCDEV} < 30\ \mu\text{A for RNGLOC} \leq 13\ \text{nmi}$$

and for

$$\text{LOCDEV} * \text{RNGLOC} < 0.091\ \text{nmi for RNGLOC} > 13\ \text{nmi}$$

The transition from angular to linear CTD criterion for transition to track prevent going to track at high values of TAE at long ranges where 30 μA represents significant linear deviation. The advantage here lies in maintaining capture mode and hence the circular nature of the capture as long as possible. However, in the event of severe crosswinds or unusually bad initialization, the possibility of turning parallel to the beam during ILSCAP exists. To provide a final safeguard against turning parallel, an override trip to track feature is also provided based on predicted TAE at the track trip point.

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*If the capture trip point lies within the "track trip" boundary, capture mode is deleted and the system transitions directly from heading mode to track mode.

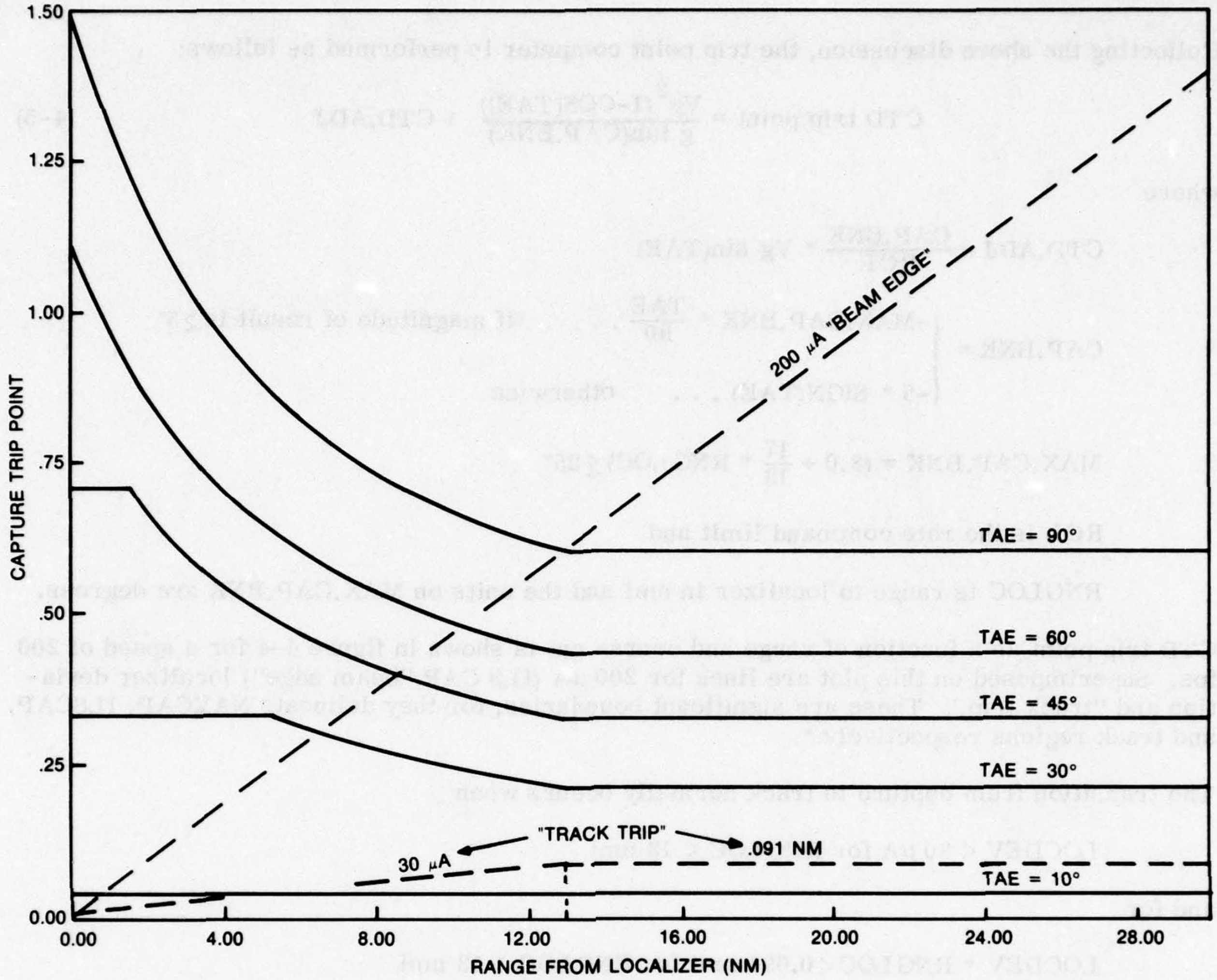


Figure 4-4. Capture Trip Point VG-200 FPS.

4.2.1.3 Final System Description

The system implementation will now be described. A block diagram of the total RNAV aided ILS localizer capture and track system is shown in figure 4-5. It should be noted that there are basically two potential capture modes. Capture computations are based on RNAV data (NAVCAP) or based on ILS data (ILSCAP). Further there is a blend-down submode (BLNDWN) of NAVCAP which is provided to fade the bank command down in the "turn short" case. If RNAV aiding is needed, the NAVCAP mode will occur first, transitioning to ILSCAP when localizer deviation becomes less than 200 μA. If during NAVCAP the system turns too far (determined by continually comparing TAE with predicted TAE at the beam edge (TAEBE) during NAVCAP), the BLDWN submode is automatically selected and fades the bank command according to the fade algorithm discussed earlier.

ILSCAP can occur in two ways. First, if NAVCAP is in progress and localizer deviation decreases below 200 μA, then ILSCAP is selected immediately. The other case occurs when the capture trip point is such that localizer deviation at that point will be less than 200 μA. In this case no RNAV aiding is needed and the ILSCAP mode is selected immediately.

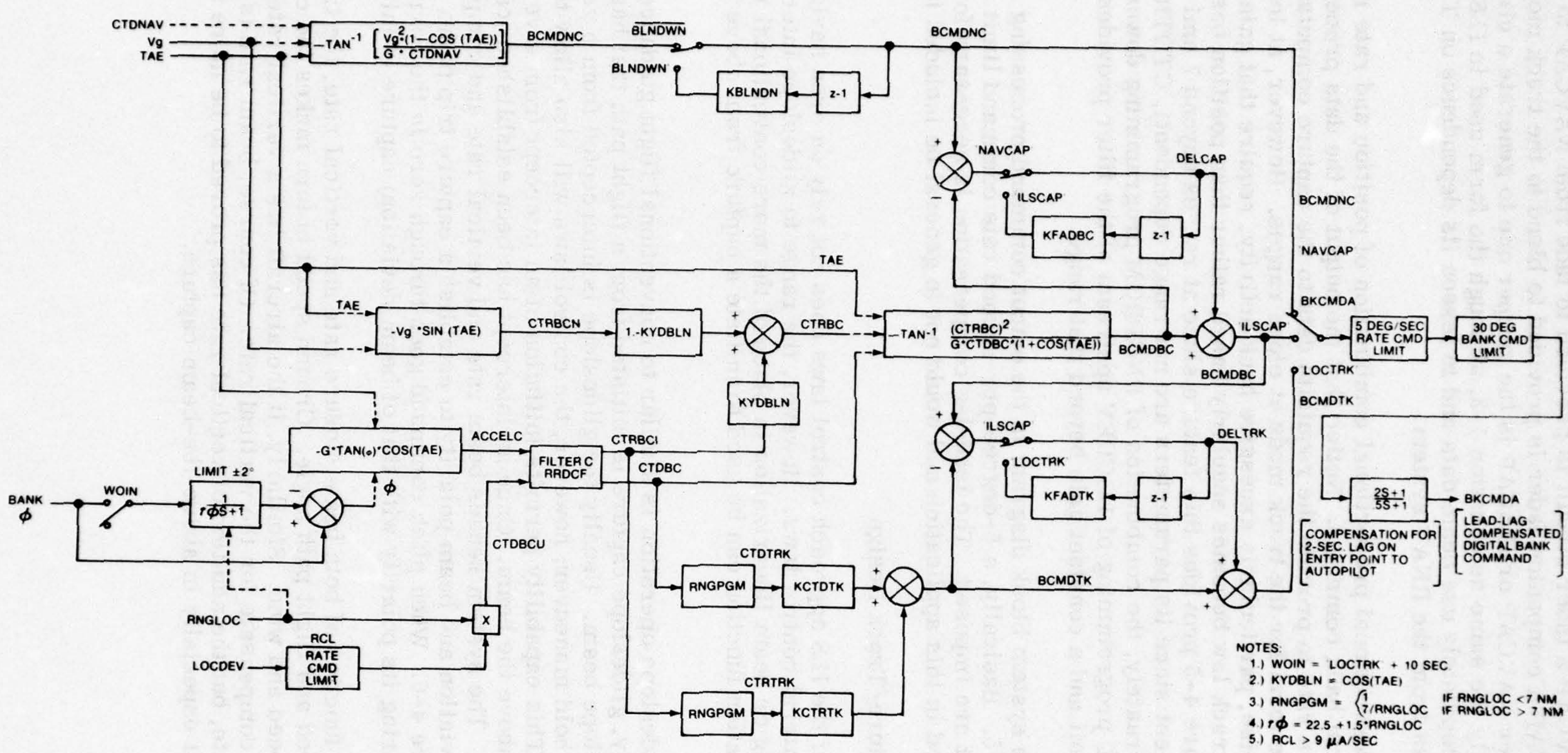


Figure 4-5. 3D/4D Lateral Axis Control Laws.

Notice that during NAVCAP a fader circuit is provided to fade from NAVCAP to ILSCAP. Similarly during ILSCAP a companion fader is provided to blend to the track mode. The bank command in either NAVCAP or ILSCAP is the proper one to generate a circular capture and both are essentially the same as equation 4-3, although the form used in ILSCAP is modified to more appropriately use beam data and to lessen its dependence on TAE and ground speed estimates from the RNAV system.

The track mode is a conventional proportional combination of position and rate relative to the beam center to form bank command. Notice that the output of the data processing filter is position and position rate to provide the requisite data to the capture computation. This is also the appropriate form for the track mode at close ranges. However, at longer ranges the effects of beam noise, particularly excessive bank activity, require that gains be softened, usually such that the track law becomes angularly based rather than position based. The RNGPGM block of figure 4-5 provides this feature since at ranges beyond 7 nmi (neglecting the filter for the moment since its parameters are not range dependent), CTDTRK is really in angular units. Alternately, the combination of RNGPRGM programming downstream of the filter and RNGLOC programming of LOCDEV upstream of the filter provides linearization of LOCDEV out to 7 nmi and a constant gain beyond that range.

The final aspect of the system block diagram is the output command processing shown at the right side of figure 4-5. Basically, a 5-degree-per-second rate command limit and a 30-degree command limit are imposed. The lead-lag compensation is necessary for the specific autopilot interface used in this application and would not in general be included in the design.

4.2.2 Glideslope Capture/Track Design

The vertical portion of the ILS approach control laws does not rely on area navigation data as heavily as do the lateral control laws. However, the range to glideslope intercept is used for radio programming or beam linearization in place of the more conventional radio altitude, and the vertical navigation function can be used to initiate a capture from above the glideslope beam.

The 3D/4D system glideslope operation is similar to conventional flight guidance computations (figure 4-6). Basically, glideslope capture is initiated from a flight path that has been set up to intercept the glideslope beam. Usually the glideslope is intercepted from a zero flight path angle or altitude hold maneuver; however, the control laws will also allow the user to capture from above. This capability permits initiation of an intercept from a vertical navigation maneuver above the beam. Once an intercept has been established, capture is completely automatic. The system senses beam rate and vertical rate and compares this mixture with beam deviation and beam polarity to establish a capture trip point. Capture logic is shown in figure 4-6. When pitch command goes through zero in the correct direction (determined by comparing its polarity with that of beam deviation) capture is initiated.

Since the capture is a function of both beam closure rate and vertical rate, the trip point is a function of ground speed and flight path angle. Ground speed in turn makes the capture a function of aircraft speed and wind. Similarly, if the aircraft has a vertical rate established, capture will adjust to compensate for the vertical rate. Of course, beam rate is also sensing this higher closure rate, but the addition of vertical rate has proved to be more accurate in adjusting the trip point especially in above-the-beam capture.

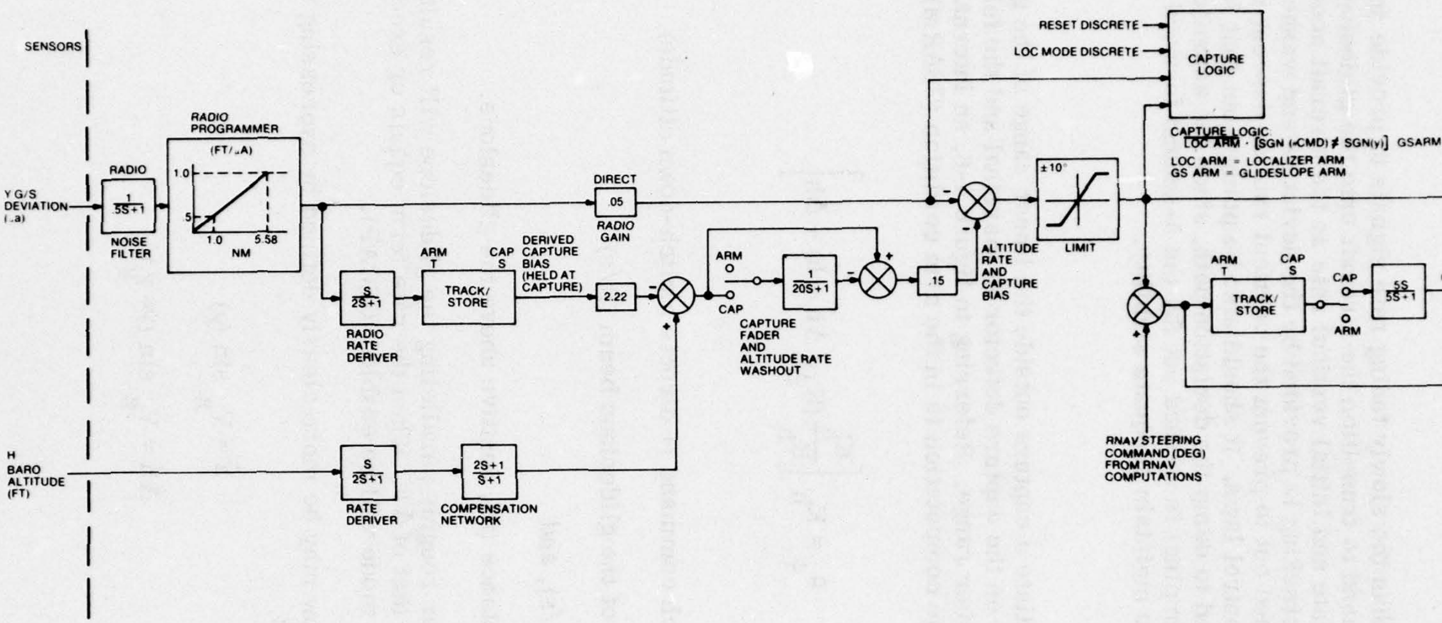


Figure 4-6. 3D/4D Longitudinal Axis Control Laws.

The capture trip point will vary as a function of how fast the glideslope beam is approached, moving further from the glideslope beam center as the closure rate increases, regardless of the reason. At capture initiation, the beam rate is memorized and held. Also, a fader or washout is initiated on both stored beam rate and vertical rate. The action is such that at the instant of capture, pitch command is zero, and the aircraft continues toward the glideslope beam.

Deviation decreases faster than the slowly fading rate signals to provide appropriately a nose-up or nose-down pitch command to transition the aircraft onto the glideslope. The fader washed out all of the beam rate and initial vertical rate as the aircraft acquires the beam center line. After capture, tracking is provided by the deviation and washed out vertical rate paths. Vertical rate is washed out to prevent the vertical rate or descent rate from causing a deviation standoff in the control laws. It should also be pointed out that for autopilot operation, vertical rate is required to damp the deviation path, since the autopilot pitch attitude (which also provides path damping) is washed out (by the 5-second forward integration) faster than normally permissible to maintain adequate stability.

4.2.1.4 Capture Trip Point

Although it is possible to initiate a capture outside the linear range of the gain programmer, the effect of the nonlinearity on the capture detector is marginal and the following discussion will assume linear programmer range. Referring to figure 4-6, an internal pitch command is formed when the glideslope computation is in the arm condition (GSARM). The value of that signal will be

$$\theta_c = K_h \left[\frac{K_{\dot{h}}}{K_h} \left(K_{\Delta \dot{h}} \, \Delta \dot{h} + \dot{h} \right) + \Delta h \right] \qquad (4\text{-}6)$$

where

θ_c = degrees of pitch command (+ directs a pitch-down attitude),

$\Delta \dot{h}$ = approach rate of the glideslope beam (ft/s),

$\dot{h}$ = ascent rate (ft/s), and

Δh = crosstrack distance (ft), positive above the glideslope.

Any flight path intersecting or roughly paralleling the glideslope will result in rate terms having a polarity opposite to that of Δh. When the rate term equals or exceeds the position term, the glideslope capture mode will be enabled (GSCAP).

The glideslope capture window may be more clearly defined by expressing the rate terms as functions of flight path angle:

$$\begin{aligned} \dot{h} &= V_g \sin(\gamma) \\ \Delta \dot{h} &= V_g \sin(\gamma - \gamma_g) \end{aligned} \qquad (4\text{-}7)$$

where

V_g = ground speed,

γ = flight path angle measured as positive counterclockwise from horizontal, and

γ_g = glideslope angle (nominally -2.5 deg).

Substituting those expressions into equation and setting $\theta_c = 0$ yields the crosstrack distance at capture as a function of flight path angle:

$$\Delta h_c = -\frac{K_{\dot{h}}}{K_h} V_g \left[K_{\dot{\Delta h}} \sin(\gamma - \gamma_g) + \sin \gamma \right] \tag{4-8}$$

This relationship is plotted in figure 4-7 for an airspeed of 200 feet per second and typical values for the other parameters. Five capture boundary lines are shown to illustrate the effect of longitudinal wind and varying glideslope angles. Since the capture window is actually determined by measured position and rate information, the capture point will be moved to compensate for along-track and crosstrack wind conditions as well as variations in glideslope angle.

Computer simulations of the system assuming various geometries and system disturbances have shown that the performance goals established for this system have been met. A limited analysis of system performance observed during the real time cockpit simulation can be found in the data analysis section of this report. A detailed analysis of the control law development and performance under wind gusts and beam noise is contained in volume 2 of this report.

4.3 RNAV CONTROL/DISPLAY FORMAT FOR ILS MODE SELECT

An additional page was created for ILS mode select. The page is accessed through the INDEX page replacing the line select for holding patterns definition. Prior to data entry, the display appears as shown in figure 4-8. The first two lines consist of pilot entered data. The data can be entered at any time; the ILS steering modules need not be resident in core. The data entries and their labels are explained below.

4.3.1 Data Entries

4.3.1.1 ILS Frequency [ILS FREQ]

The frequency entry requires a valid ILS frequency. If the frequency entered is not an ILS frequency (as defined in table 4-1), an error message appears in the scratch pad alternately with the invalid data and the data entry is not allowed. Frequency is changed only by overwriting with a valid ILS frequency.

Table 4-1. Allowable ILS Frequencies in MHz.

108.10	109.10	110.10	111.10
108.15	109.15	110.15	111.15
108.30	109.30	110.30	111.30
108.35	109.35	110.35	111.35
108.50	109.50	110.50	111.50
108.55	109.55	110.55	111.55
108.70	109.70	110.70	111.70
108.75	109.75	110.75	111.75
108.90	109.90	110.90	111.90
108.95	109.95	110.95	111.95

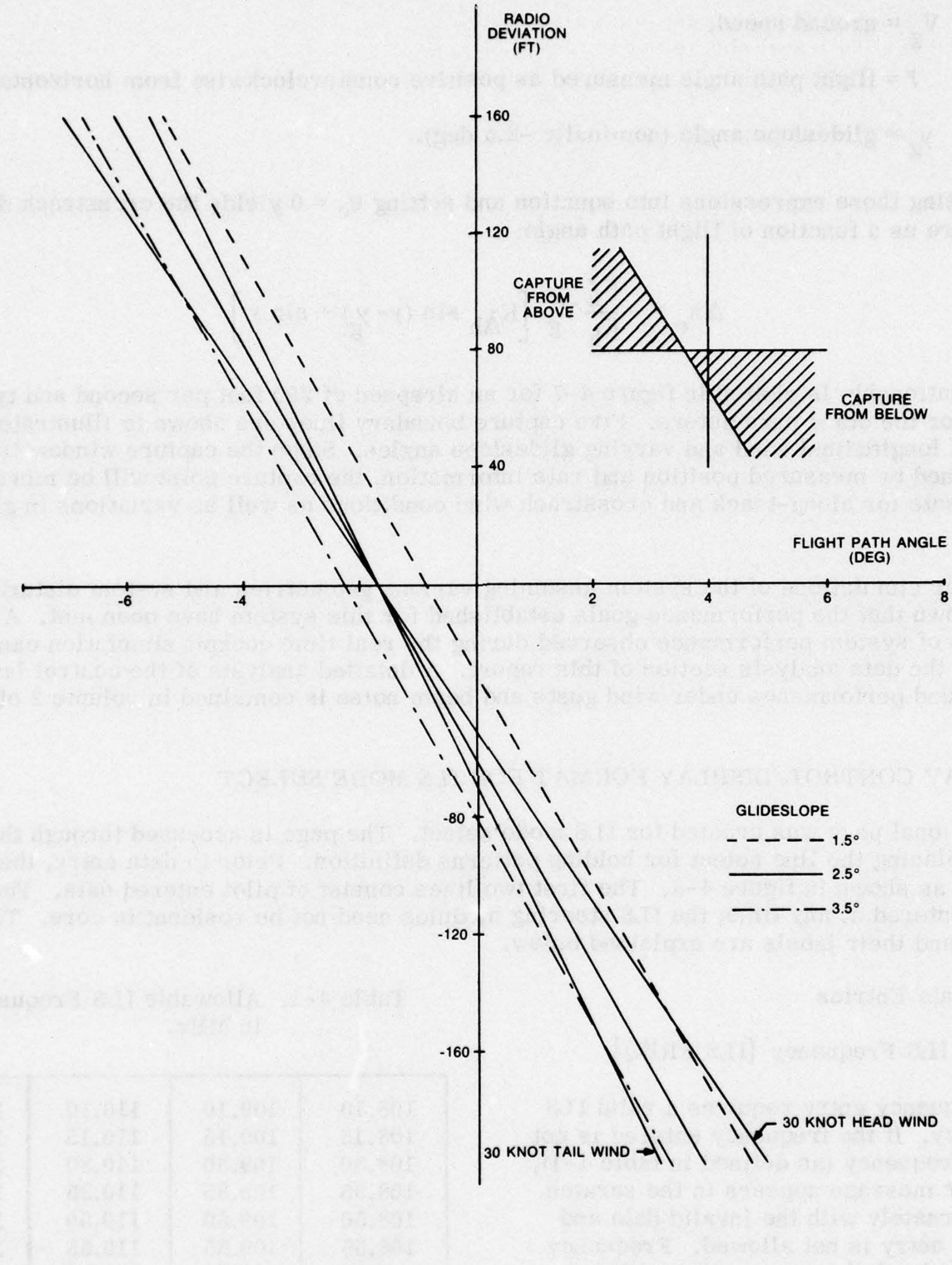


Figure 4-7. Glideslope Capture Boundary.

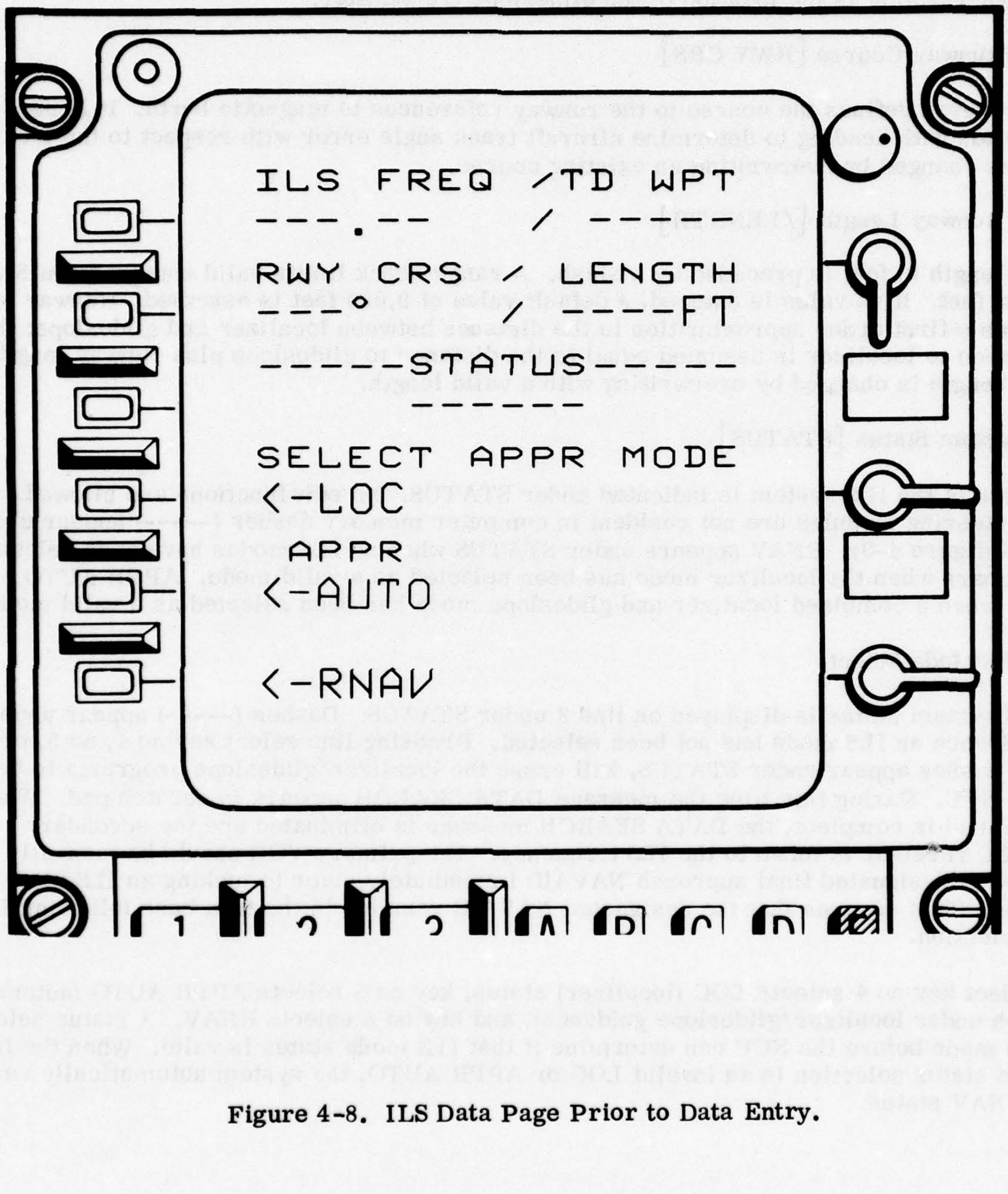


Figure 4-8. ILS Data Page Prior to Data Entry.

4.3.1.2 Touchdown Waypoint [/TD WPT]

The touchdown waypoint identifier must be preceded by a slash. The waypoint must also be in the flight plan at the time of entry; else the data entry is disallowed and an error message is displayed alternately with the invalid ident. The system assumes that the location of the touchdown waypoint is the location of the glideslope transmitter.

4.3.1.3 Runway Course [RWY CRS]

Runway course defines the course to the runway referenced to magnetic north. It is used in combination with heading to determine aircraft track angle error with respect to the localizer. Course is changed by overwriting an existing course.

4.3.1.4 Runway Length [/LENGTH]

Runway length in feet is preceded by a slash. A range check limits valid entries from 5,000 to 16,000 feet. If no value is entered, a default value of 9,000 feet is assumed. Runway length is used as a first order approximation to the distance between localizer and glideslope; thus, the distance to localizer is assumed equal to the distance to glideslope plus runway length. Runway length is changed by overwriting with a valid length.

4.3.2 System Status [STATUS]

The status of the ILS system is indicated under STATUS. No edit functions are allowed. When the ILS steering modules are not resident in computer memory dashes (-----) appear under STATUS (figure 4-9). RNAV appears under STATUS when no ILS modes have been selected. LOC appears when the localizer mode has been selected as a valid mode. APPR AUTO appears when a combined localizer and glideslope mode has been selected as a valid mode.

4.3.3 ILS Mode Select

The ILS system status is displayed on line 3 under STATUS. Dashes (-----) appear under STATUS when an ILS mode has not been selected. Pressing line select key no 4, no 5, or no 6, when dashes appear under STATUS, will cause the localizer/glideslope programs to be read into the NCU. During this time the message DATA SEARCH appears in scratch pad. When the data load is complete, the DATA SEARCH message is eliminated and the secondary VOR/LOC receiver is tuned to the ILS frequency. The primary VOR should be manually tuned to the designated final approach NAVAID immediately prior to making an ILS mode selection. This ensures that the designated NAVAID remains in the data base following ILS mode selection.

Line select key no 4 selects LOC (localizer) status, key no 5 selects APPR AUTO (automatic approach under localizer/glideslope guidance), and key no 6 selects RNAV. A status selection must be made before the NCU can determine if that ILS mode status is valid. When the initial ILS page status selection is an invalid LOC or APPR AUTO, the system automatically reverts to the RNAV status.

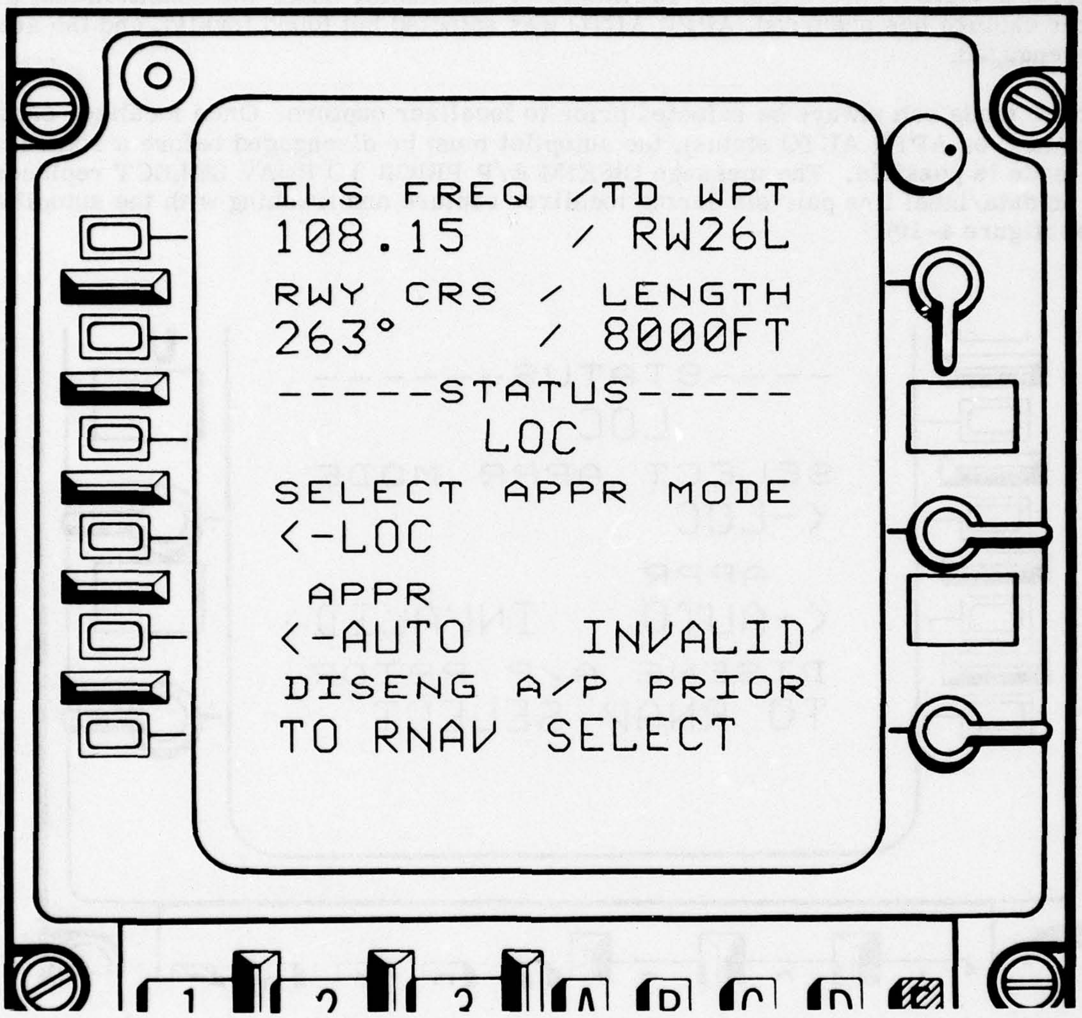


Figure 4-9. ILS Data Page During ILS Program Roll-in.

If the selected status is valid, the STATUS display will change to the selected status (LOC, APPR AUTO, or RNAV). If the selected status is invalid, the message INVALID appears next to the line select, the last valid status remains in effect, and the STATUS display remains unchanged. The INVALID message is removed when the mode becomes valid or when another line select key is pressed. When LOC or APPR AUTO is the valid status, the HSI course arrow slews to the runway heading and raw localizer deviation is displayed on the HSI lateral deviation bar. Figure 4-10 illustrates the display under the condition that the localizer capture has occurred, APPR AUTO was selected but found invalid, and the autopilot is engaged.

The RNAV mode can always be selected prior to localizer capture. Once localizer capture occurs (LOC or APPR AUTO status), the autopilot must be disengaged before a return to the RNAV mode is possible. The message DISENG A/P PRIOR TO RNAV SELECT replaces RNAV on data/label line pair six during localizer capture and tracking with the autopilot engaged (figure 4-10).

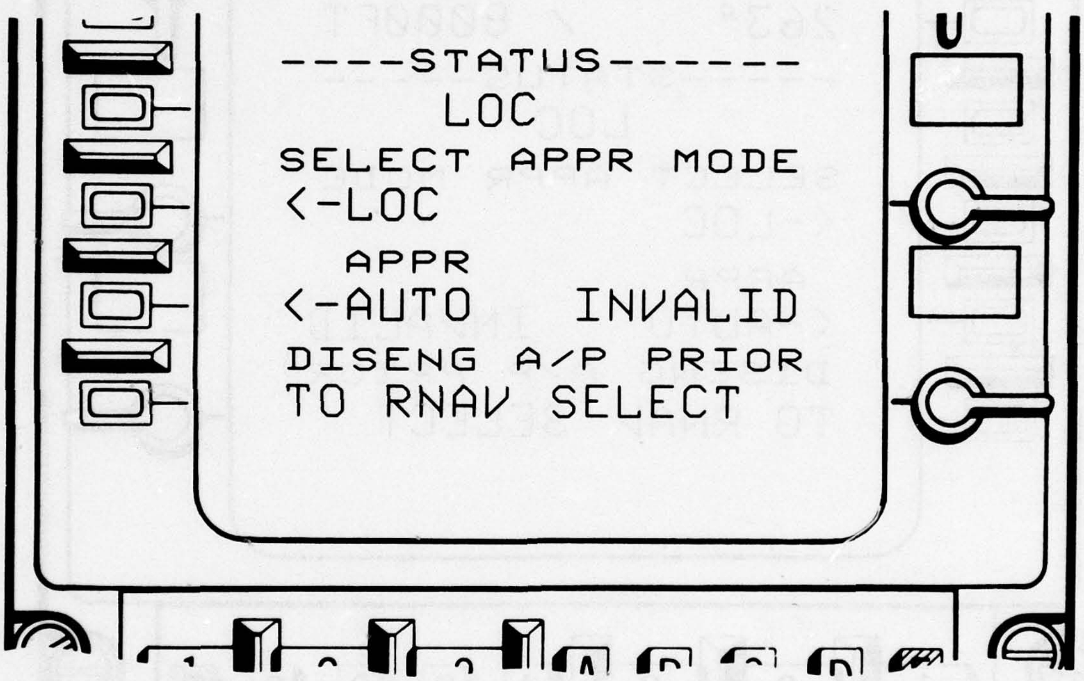


Figure 4-10. RNAV Inhibit Display.

When in the ILS mode with RNAV status, the message PUSH TO RELOAD RNAV DATA appears in data/label line pair six (figure 4-11). Pushing line select key no 6 reloads RNAV data into the NCU and takes the system out of the ILS mode. During this time, the message DATA SEARCH appears in scratch pad. The message DATA SEARCH will disappear from scratch pad when the data load is complete. Dashes appear under STATUS and the system returns to a non-ILS mode.

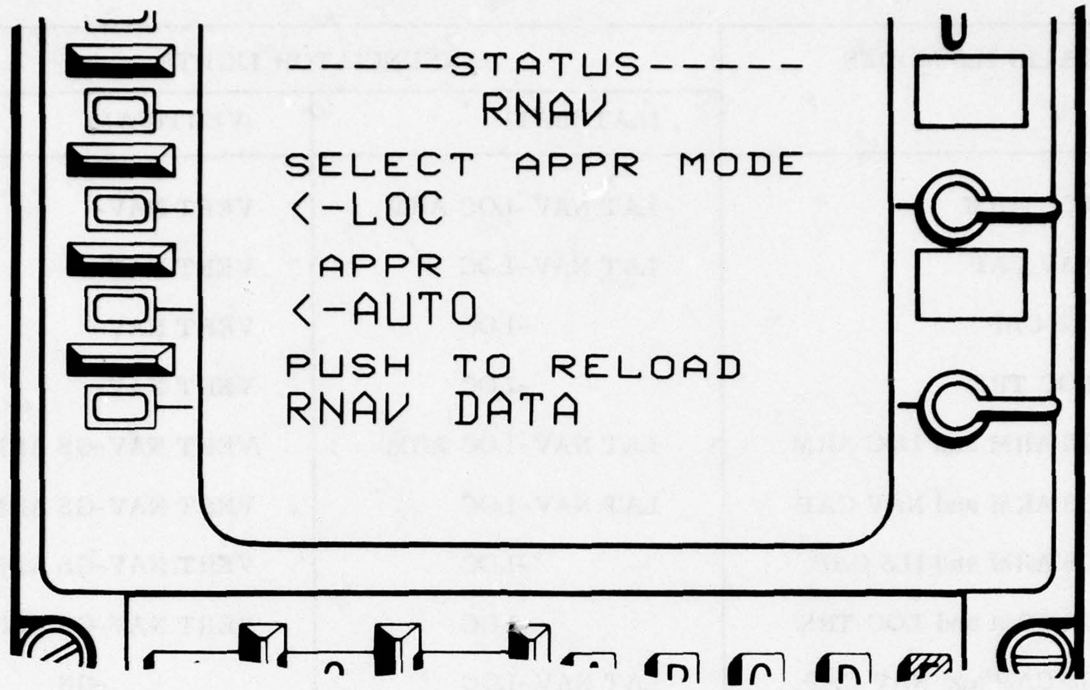


Figure 4-11. ILS Data Page Prior to ILS Program Roll-Out.

4.4 ILS MODE ANNUNCIATOR LOGIC

The 3D/4D CRT control display unit was found acceptable for selection of the ILS mode. However a mode display on the instrument panel was felt to be necessary. The mode annunciator shown in figure 4-12 was developed for this purpose. Each of the four display locations indicate up to three messages (one at a time). Presently six messages are displayed (along with blanks). The messages corresponding to valid ILS modes are shown in table 4-2. The messages are described in the following paragraphs.

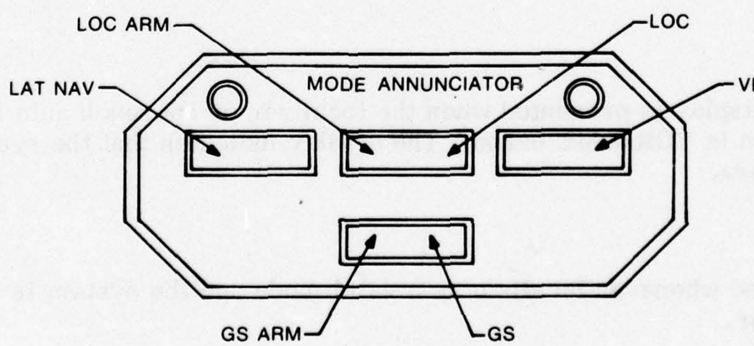


Figure 4-12. 3D/4D/ILS Mode Annunciator.

Table 4-2. Annunciator Logic.

VALID ILS MODES	ANNUNCIATOR LIGHTS	
	(LATERAL)	(VERTICAL)
LOC ARM	LAT NAV-LOC ARM	VERT NAV-
NAV CAP	LAT NAV-LOC	VERT NAV-
ILS CAP	-LOC	VERT NAV-
LOC TRK	-LOC	VERT NAV-
GS ARM and LOC ARM	LAT NAV-LOC ARM	VERT NAV-GS ARM
GS ARM and NAV CAP	LAT NAV-LOC	VERT NAV-GS ARM
GS ARM and ILS CAP	-LOC	VERT NAV-GS ARM
GS ARM and LOC TRK	-LOC	VERT NAV-GS ARM
GS CAP and NAV CAP	LAT NAV-LOC	-GS
GS CAP and ILS CAP	-LOC	-GS
GS CAP and LOC TRK	-LOC	-GS

4.4.1 LAT NAV

Lateral navigation is indicated when VOR/DME based data is used by the RNAV system to derive the lateral steering data for autopilot or flight director steering. It is not displayed when the RNAV system is not being used for flight or when localizer data is used for lateral navigation.

4.4.2 LOC ARM

The localizer arm display is presented when the localizer or approach auto is a valid mode but lateral navigation is VOR/DME based. The display indicates that the system is armed for a localizer capture.

4.4.3 LOC

Localizer is indicated whenever localizer is a valid mode and the system is capturing or tracking the localizer.

4.4.4 VERT NAV

Vertical navigation is indicated when VOR/DME/barometric altitude based data is used by the 3D RNAV system to derive the vertical steering data for autopilot or flight director steering. It is not displayed when the RNAV system is not being used for flight or when glideslope data is used for vertical navigation.

4.4.5 GS ARM

The glideslope arm display is presented when approach auto is a valid mode, but vertical navigation is VOR/DME/barometric altitude based. The display indicates that the system is armed for a glideslope capture.

4.4.6 GS

Glideslope is indicated whenever approach auto is a valid mode and the system is capturing or tracking the glideslope.

Cockpit Simulation Experiments

A limited real-time cockpit simulation was undertaken for proof of concept, final software checkout, and performance verification. The simulation facility consisted of (1) a hybrid computer for modeling the G-1 aircraft and autopilot dynamics, synthesizing sensor data, and recording experimental data; (2) a cockpit mockup consisting of typical cockpit indicators and controls for evaluating manual flight control; and (3) the 3D/4D area navigation system. The hybrid computer and cockpit mockup is described in detail in paragraph 5.1. The 3D/4D system was described in the preceding sections.

The simulated terminal area experiments closely followed those flown in the first phase. Modifications were incorporated to reflect revised 4D approach procedures and equipment capabilities. A complete description of the experiments is found in the following paragraphs.

5.1 SIMULATION FACILITY

The hybrid computer was used to perform the following tasks: (1) model the aircraft and autopilot dynamics, (2) synthesize sensor data and model the errors in the navigation sensors (VOR, DME, etc), and (3) monitor the experiment and record data.

The cockpit mockup provided the setting for the experiment. It contains the necessary indicators and controls so that the pilot can experience the significant aspects of flying an aircraft.

Figure 5-1 provides a diagram of the equipment used, functions performed, and data flow.

5.1.1 Simulation Equipment Description

5.1.1.1 Hybrid Computer, Analog Portion

Type: EAI 680

Manufacturer: Electronic Associates, Inc., Long Branch, New Jersey

Total number of amplifiers: 120

Number of integrators: 48

5.1.1.2 Hybrid Computer, Digital Portion

Type: EAI 640 (also referred to as Pacer 100)

Manufacturer: EAI

Core storage size: 32,768 words, each 16 bit

A special digital input/output capability has been added to permit communication with the dynamic test adapter.

5.1.1.3 Cockpit

The cockpit mockup is based on a Boeing 727. The major instruments are an HSI (Collins type 331A-8D-002) and ADI (329B-8J). The remaining instruments are baroaltimeter, air-speed indicator, vertical speed indicator, turn and bank indicator, and a percent power indicator.

The controls (pedals, wheel, column, and throttle) are electrically connected to the analog computer so that the pilot can manually fly the airplane.

An audio link is used to permit communications between the pilot and the air traffic controller.

Figure 5-2 is a view of the cockpit showing the instruments, controls, and area navigation equipment.

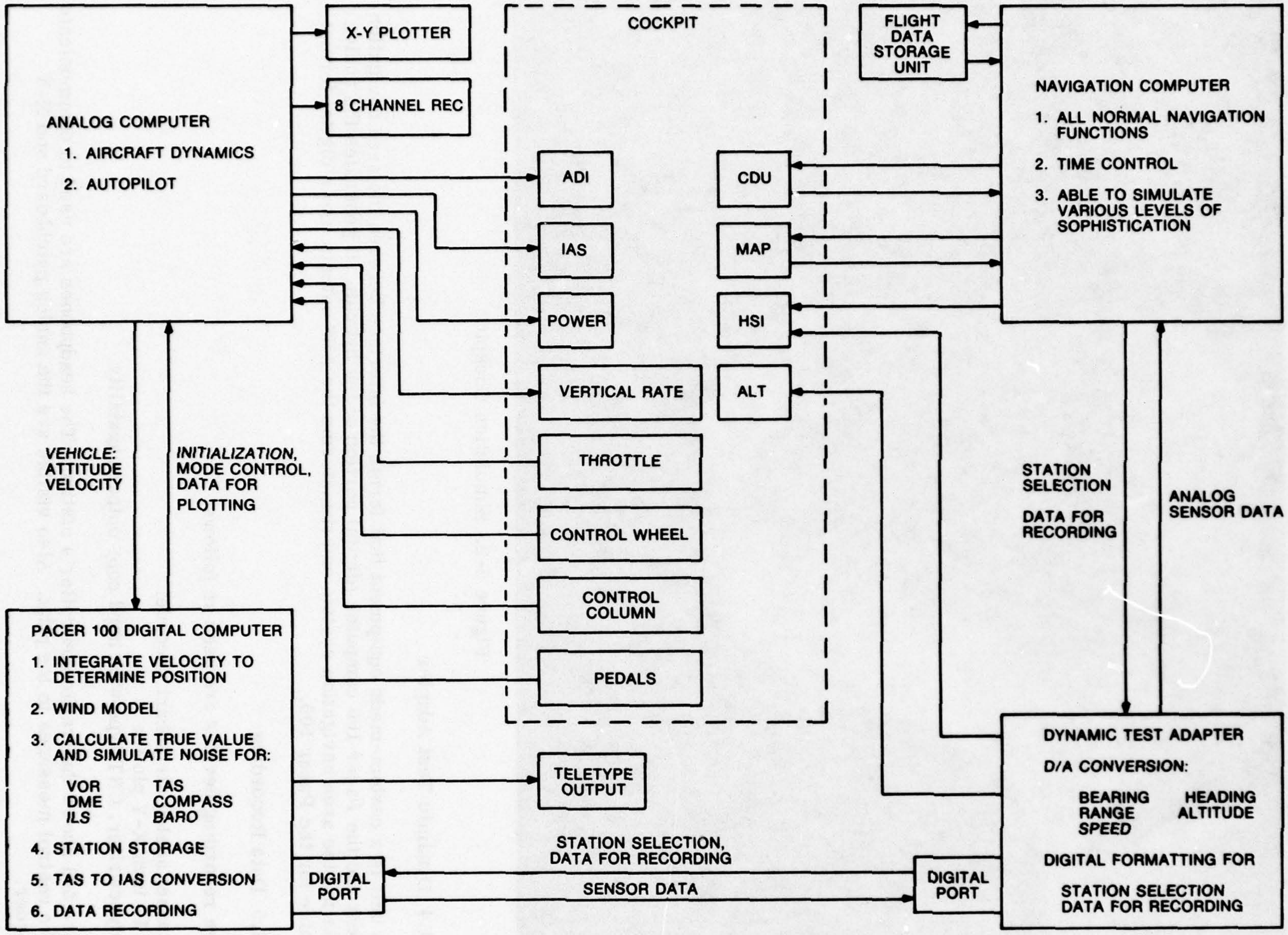


Figure 5-1. 3D/4D Simulation Diagram.

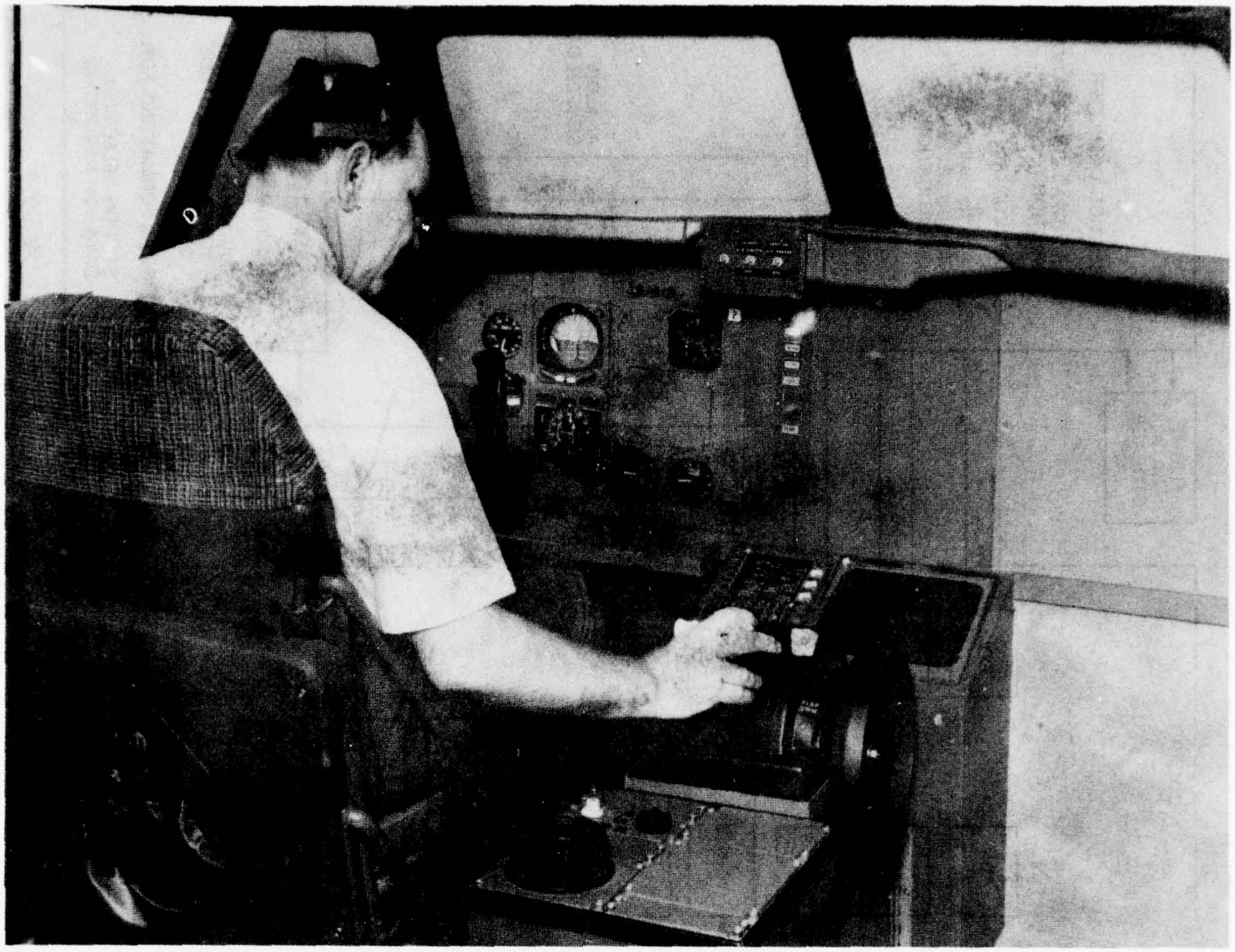


Figure 5-2. Simulation Cockpit.

5.1.1.4 Dynamic Test Adapter

This unit is a custom-made equipment that forms the interface between the area navigation system and the Pacer 100 computer (digital portion of the hybrid). It generates the analog inputs for the area navigation system and transforms the ANS outputs into a digital format suitable for the Pacer 100.

5.1.1.5 Data Recording

Three recording devices are used as follows:

8-channel analog stripchart recorder
11 x 17 inch X-Y plotter
Teletypewriter, CRT type with hard copy output capability

Figure 5-3 shows the traffic controller's station. The headphones are used to communicate traffic control messages to the pilot. Also visible are the analog patchboard and X-Y recorder.

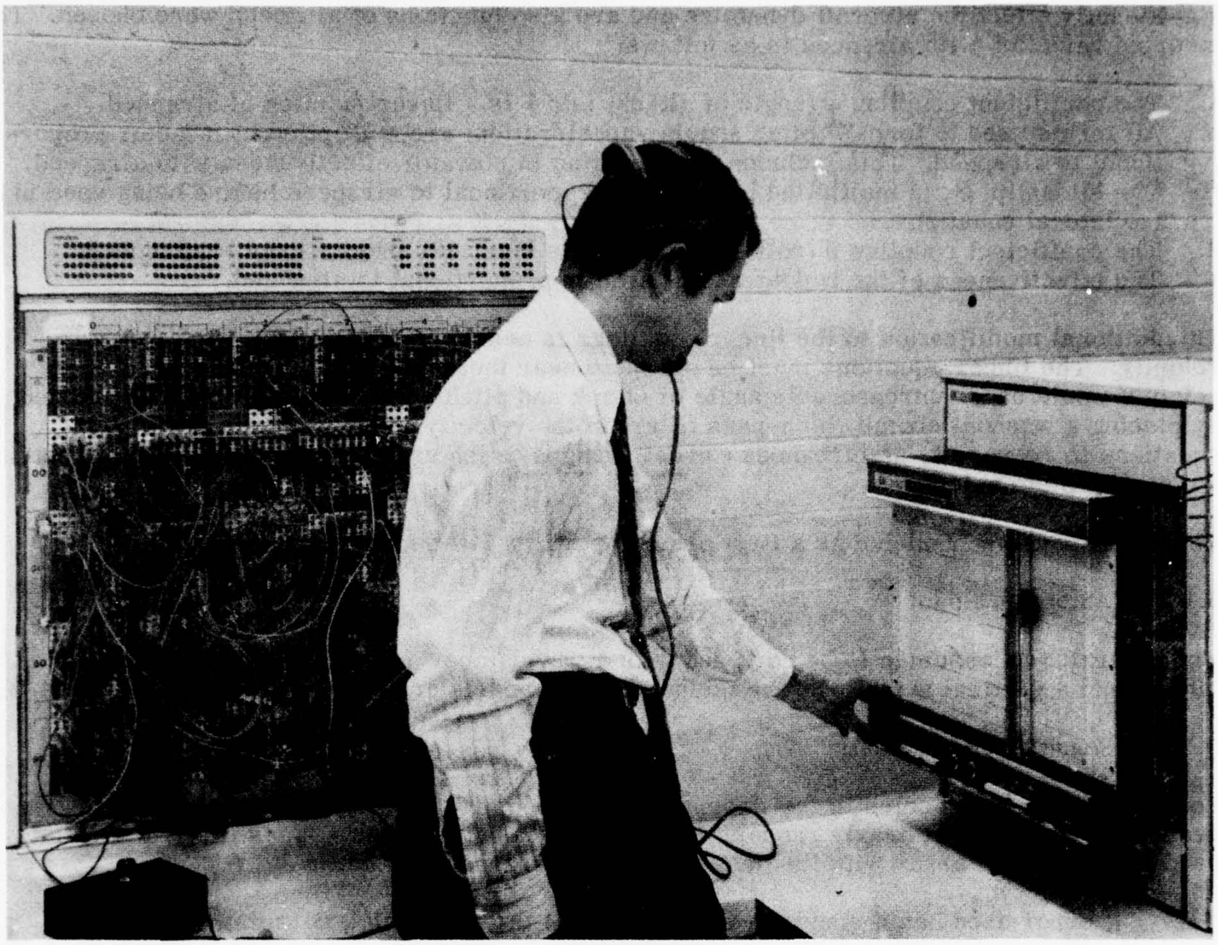


Figure 5-3. Traffic Controller Station.

5.1.2 Simulation Models

5.1.2.1 Aircraft Model

Grumman G-I aircraft with the Sperry SP40C autopilot was modeled as the flight test program would utilize this aircraft. Linearized equations of motion were used as the basis for the simulation. Some of the coefficients were adjusted as a function of airspeed. Special treatment was given to the airspeed equation to permit simulation of a wide range of airspeeds.

The decision to use linearized equations (rather than total aircraft equations) was made because these equations: (1) permit accurate analysis at one flight condition, (2) permit wind gust studies, (3) operate adequately over the wide dynamic range needed in the 3D/4D studies, and (4) are the basis of much similar work done at Collins over the years that could be drawn upon.

Some of the coefficients were parameterized as functions of airspeed. Only coefficients that significantly affect the aircraft dynamics and are also functions of airspeed were chosen. The modeled variation with airspeed is as follows:

a. The coefficient coupling α (angle of attack) into $\dot{\alpha}$ is a linear function of airspeed.
b. All terms used to form $\ddot{\theta}$ (pitch angular acceleration) are multiplied by a factor proportional to airspeed. This includes the variation in elevator effectiveness with airspeed.
c. The slideslip, β, is multiplied by a factor proportional to airspeed before being used in the lateral equations.
d. The coefficient coupling ϕ (roll angle) into $\dot{\beta}$ is inversely proportional to airspeed.
e. The effectiveness of the rudder and aileron is proportional to airspeed.

An additional modification to the linear equations is necessary to permit a wide range in velocity. The linear equations must be operated near their null point. Otherwise, a large velocity would cause unreasonable angle of attack and pitch angle. This problem is avoided by placing a washout circuit (high-pass filter) in the velocity equation. This permits the equations to respond to disturbances (thrust changes, pitch angle changes) and yet not retain the steady-state value.

Engine response is modeled as a first order lag with a 1.6-second time constant.

5.1.2.2 Autopilot Model

The aircraft was assumed to be equipped with a yaw damper and turn coordination. Both a lateral and a vertical autopilot were included. The models are shown in figures 4-1 and 4-2.

5.1.2.3 Sensor Error Models

Sensor errors are modeled in the Pacer 100 digital computer. An algorithm is used to generate a sequence of nearly random numbers (white noise). A low-pass filter is then used to produce an error with the desired spectral characteristics.

The VOR error used has a standard deviation of 1.4 degrees with a correlation time of 10 seconds. The magnitude is derived by assuming a ground station error of 1.9 degrees, (2σ) and an airborne receiver error of 2 degrees, (2σ).

The DME error has a standard deviation of 0.11 nautical mile, with a correlation time of 300 seconds. This is based on a ground station error of 0.1 nmi, 2σ, and an airborne equipment error of 0.2 nmi, 2σ.

All other sensors (airspeed, altitude, and heading) are modeled with zero error.

5.2 TIME CONTROL EXPERIMENTS

5.2.1 4D Terminal Area Paths

The time control experiments were simulated using a proposed 1982 Denver terminal area route design (figure 5-4) (ref 13). The west flow was selected since it utilizes the predominant ILS approach runway (runway 26L). Arrivals from the south are simulated since the base leg maneuvering area is narrower (than from the north) implying a more taxing controller/pilot situation. The approach from the southwest represents a lengthy approach with a maximum number of turns. Conversely, the approach from the southeast is short with a minimum amount of maneuver area.

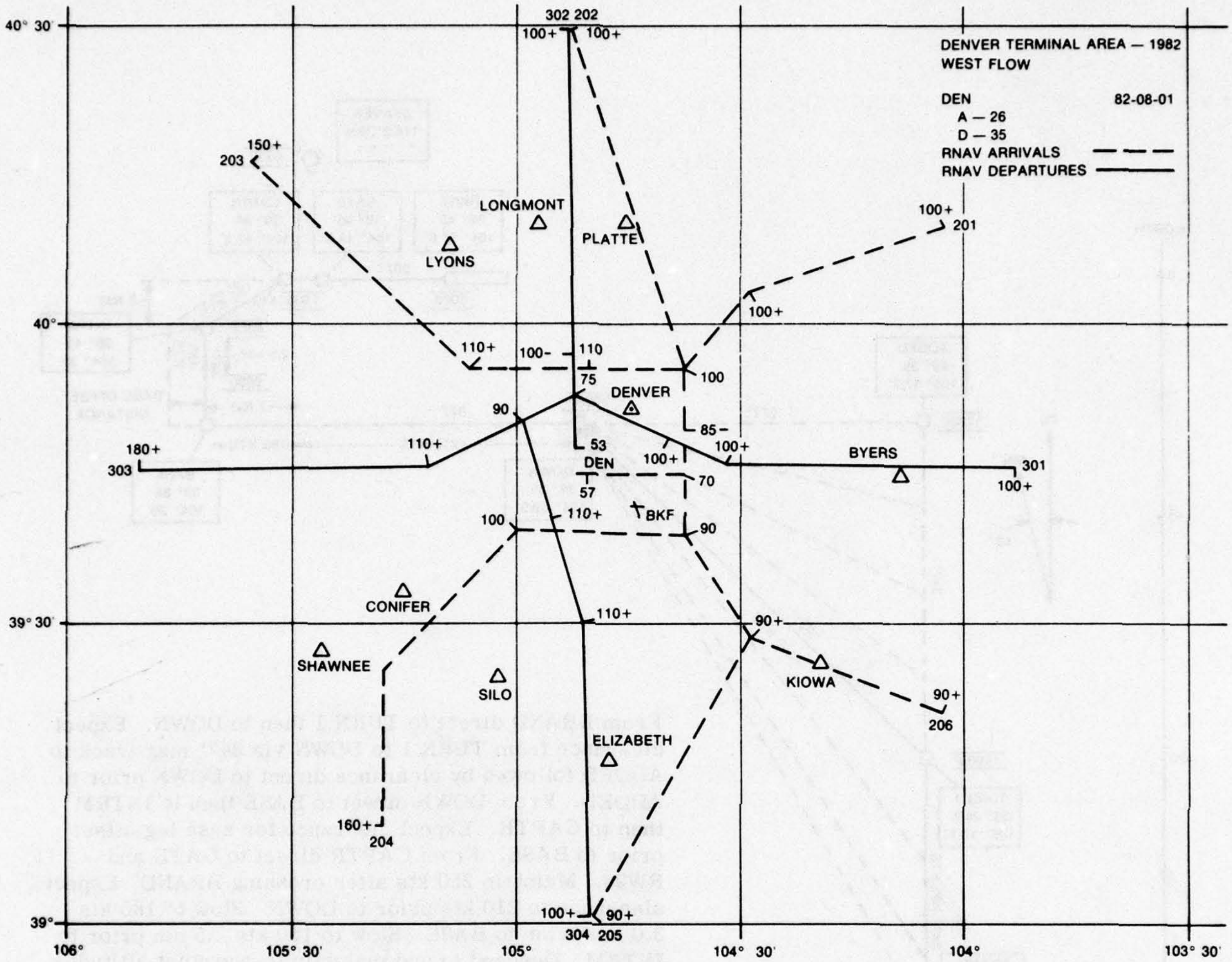


Figure 5-4. Denver Terminal Area - 1982 West Flow.

Figure 5-5 illustrates the southwest RNAV standard terminal arrival route named BRAND. A delay fan and path shortening area are provided early in the approach for initial path adjustments. Base leg extensions are used for fine tuning prior to final approach. Nominal airspeeds consist of entry at 250 knots and a slowdown to 210 knots somewhere in the delay fan prior to DOWN. The 210-knot clean aircraft configuration airspeed is maintained until the turn-to-base leg. The slowdown to final approach speed is provided just prior to the localizer capture leg. Speed changes are assumed to occur at the rate of 40 knots/min and effected prior to crossing the waypoint.

Lower speeds were utilized for the general aviation experiments. Figure 5-6 illustrates the low speed BRAND approach. Slowdown to 110 knots was initiated, 1.6 nmi prior to BASE; the slowdown to 90 knots was initiated 1 nmi prior to INTRM.

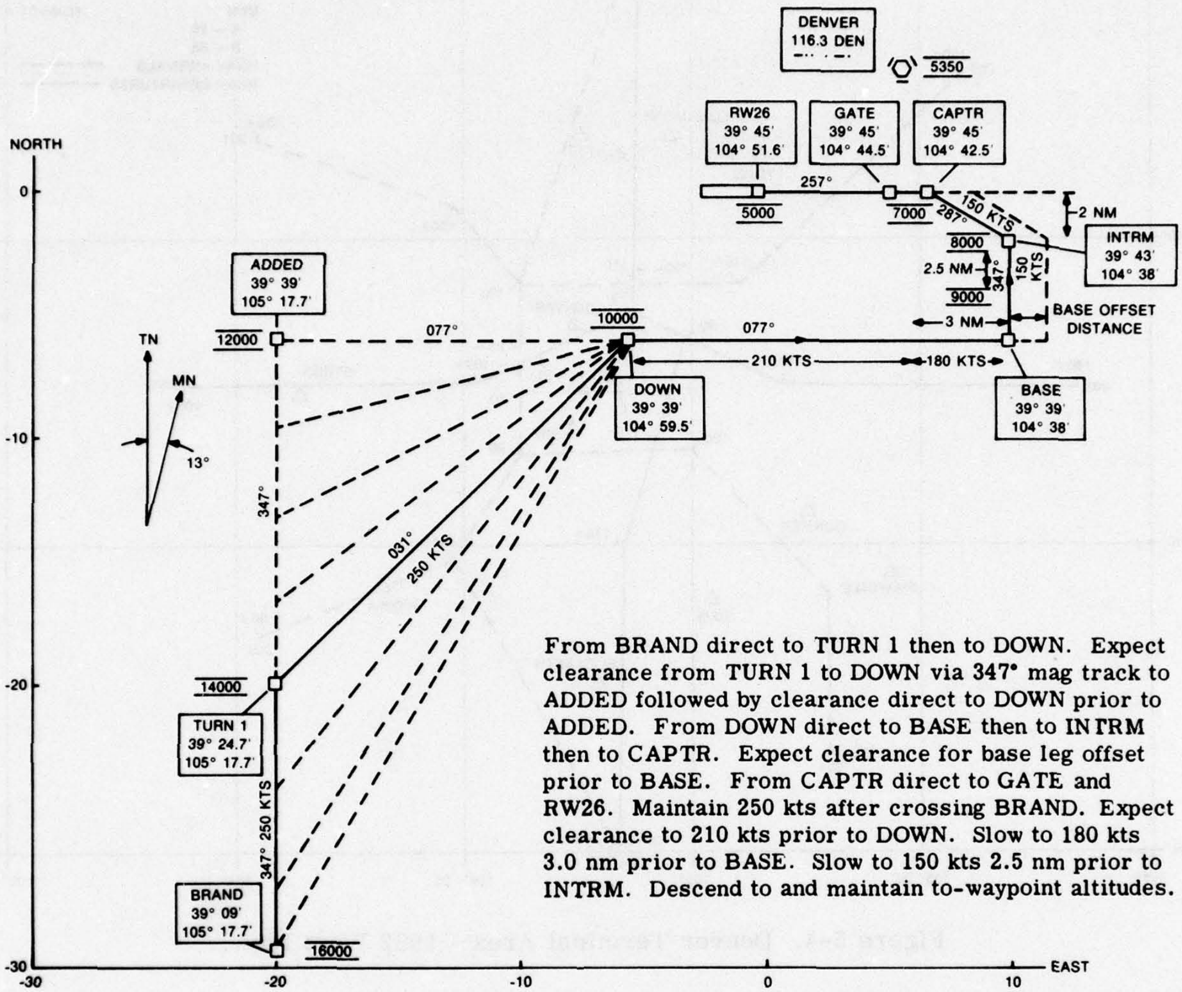
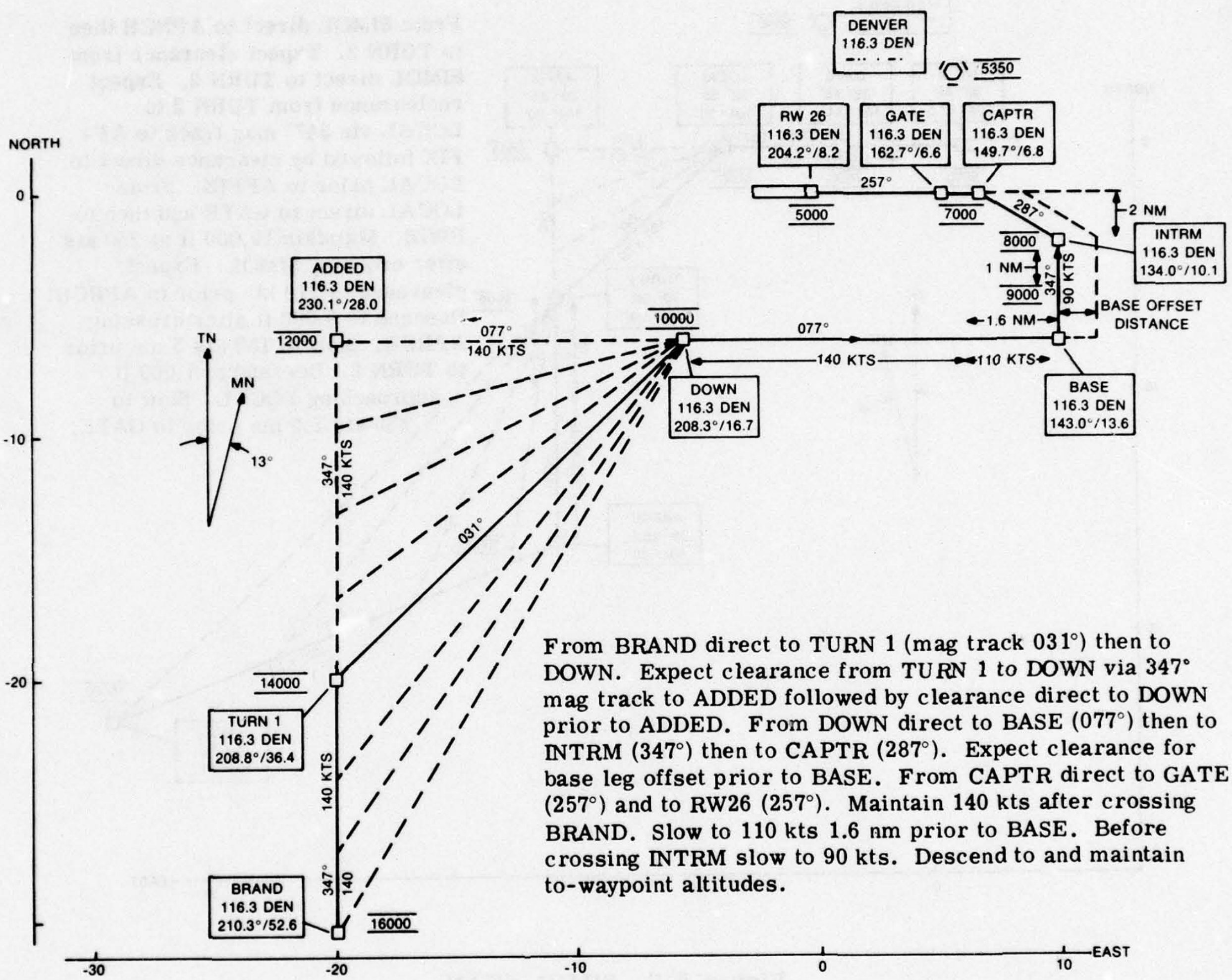


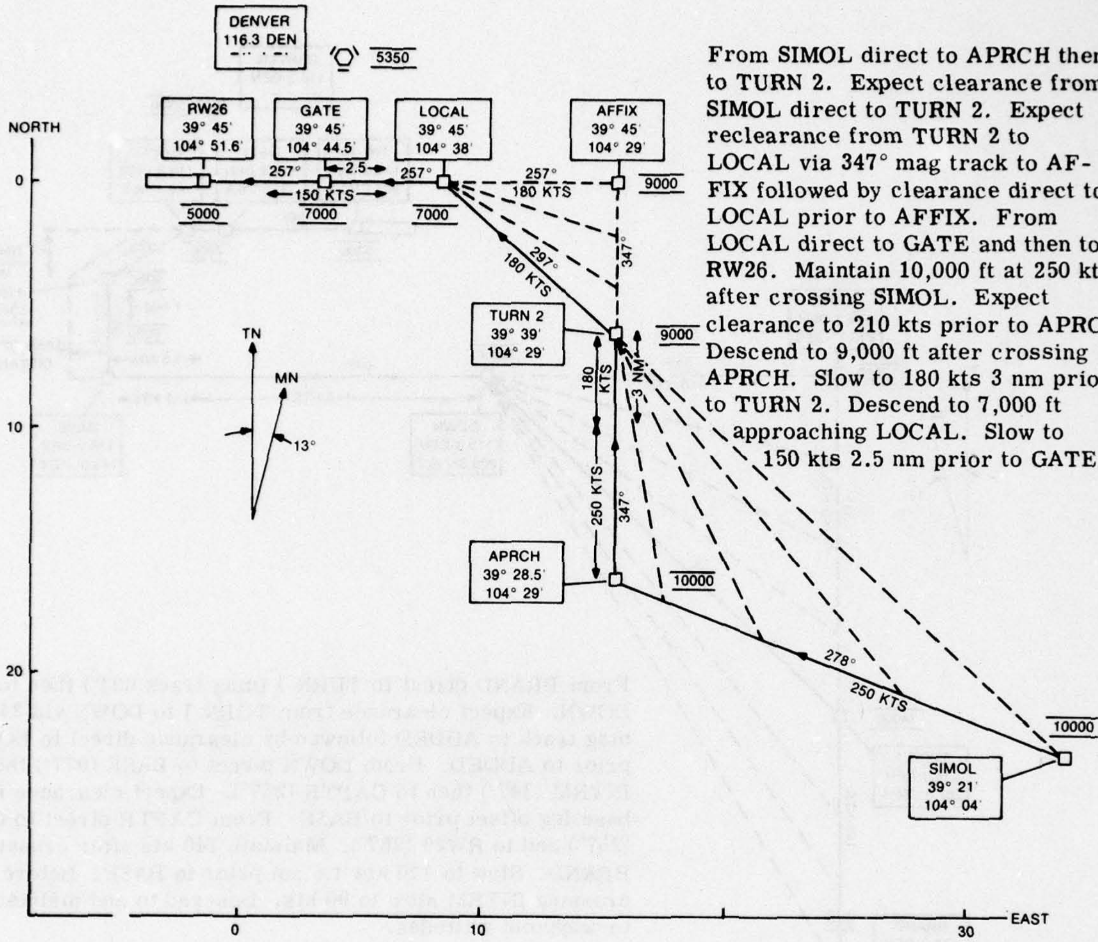
Figure 5-5. BRAND STAR.



From BRAND direct to TURN 1 (mag track 031°) then to DOWN. Expect clearance from TURN 1 to DOWN via 347° mag track to ADDED followed by clearance direct to DOWN prior to ADDED. From DOWN direct to BASE (077°) then to INTRM (347°) then to CAPTR (287°). Expect clearance for base leg offset prior to BASE. From CAPTR direct to GATE (257°) and to RW26 (257°). Maintain 140 kts after crossing BRAND. Slow to 110 kts 1.6 nm prior to BASE. Before crossing INTRM slow to 90 kts. Descend to and maintain to-waypoint altitudes.

Figure 5-6. BRAND STAR - Low Speed.

The southeast RNAV standard terminal arrival route (named SIMOL) is shown in figure 5-7. Path shortening is provided early in the approach. Delaying the aircraft is initially accomplished by slowing the aircraft to 110 knots prior to TURN 2. Fine tuning is provided by means of path/speed control over the delay fan to LOCAL.



From SIMOL direct to APRCH then to TURN 2. Expect clearance from SIMOL direct to TURN 2. Expect reclearance from TURN 2 to LOCAL via 347° mag track to AFFIX followed by clearance direct to LOCAL prior to AFFIX. From LOCAL direct to GATE and then to RW26. Maintain 10,000 ft at 250 kts after crossing SIMOL. Expect clearance to 210 kts prior to APRCH. Descend to 9,000 ft after crossing APRCH. Slow to 180 kts 3 nm prior to TURN 2. Descend to 7,000 ft approaching LOCAL. Slow to 150 kts 2.5 nm prior to GATE.

Figure 5-7. SIMOL STAR.

The low speed SIMOL STAR is shown in figure 5-8. The charted approach speeds for these STAR's are similar to the charted speeds for the BRAND STAR's.

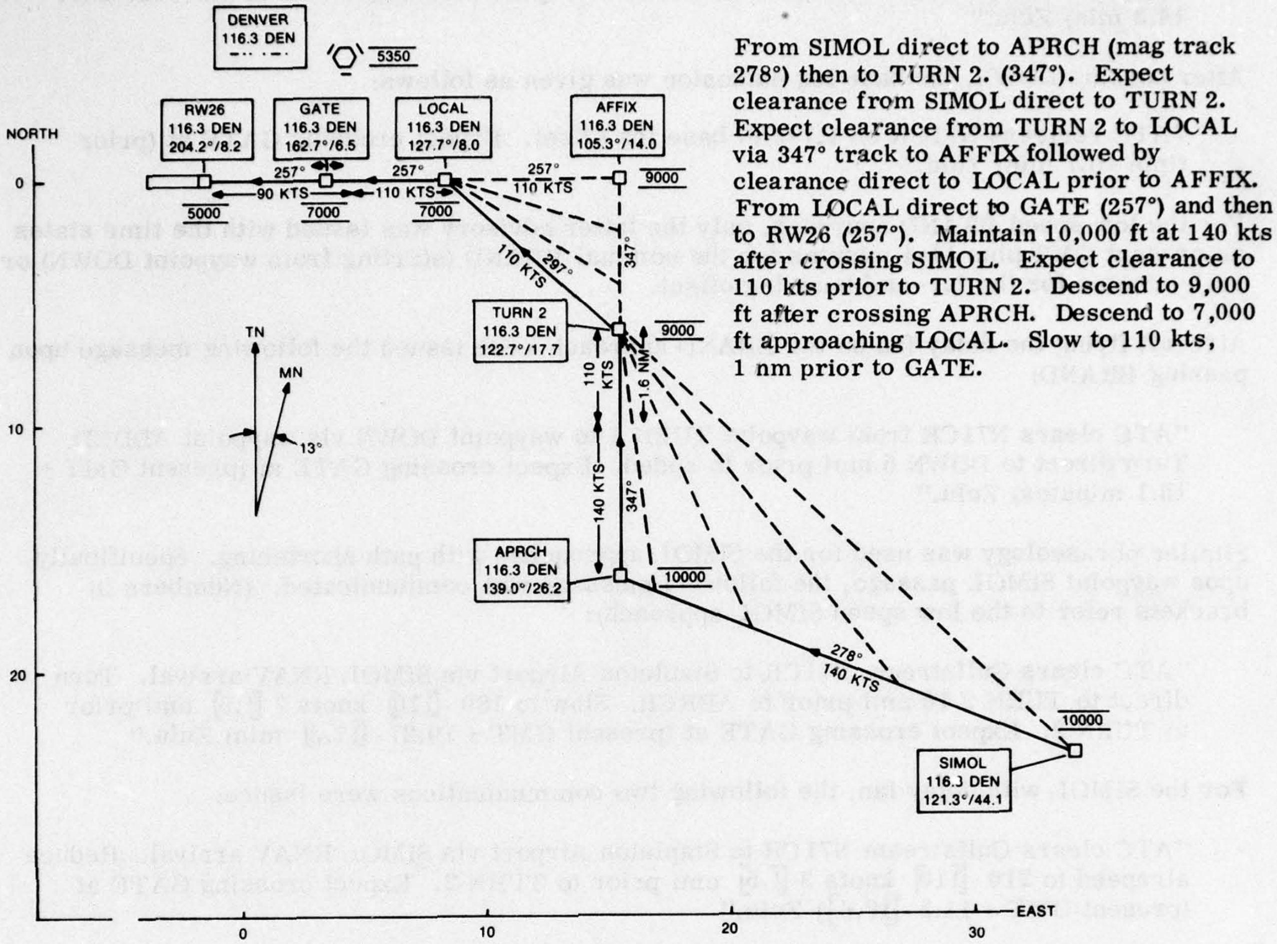


Figure 5-8. SIMOL STAR - Low Speed.

5.2.2 Air Traffic Control Procedures

Eight different approaches were controlled with the BRAND and SIMOL STAR's defined earlier. They consisted of a BRAND approach with a base leg offset, a BRAND approach with delay fan, a SIMOL approach with delay fan, and a SIMOL approach with path shortened. These approaches were flown both on the high and low speed STAR's. Simulations utilizing the low speed BRAND STAR's were initiated at waypoint DOWN instead of waypoint BRAND to reduce some of the flight time. Nominal flight times were about 10 minutes for high speed SIMOL and low speed BRAND (starting from waypoint DOWN), 15 minutes for high speed BRAND and 20 minutes for low speed SIMOL.

On the BRAND approach with base leg extension, the phraseology used upon entry was as follows:

"ATC clears Gulfstream N71CR to Stapleton Airport via BRAND RNAV arrival. Reduce airspeed to 210 knots 5 nmi prior to DOWN. Expect crossing GATE at (present GMT + 14.3 min) Zulu."

After passing DOWN, the base leg extension was given as follows:

"ATC reclears N71CR on 1.1-nmi base leg offset. Expect crossing GATE at (prior time +0.7 min) Zulu."

For the low speed BRAND approach, only the latter advisory was issued with the time states as present GMT plus 11.4 minutes for the nominal BRAND (starting from waypoint DOWN) or 12.5 minutes for the 1.1-nmi base leg offset.

Aircraft flying the delay fan on the BRAND approach were issued the following message upon passing BRAND:

"ATC clears N71CR from waypoint TURN 1 to waypoint DOWN via waypoint ADDED. Turn direct to DOWN 5 nmi prior to added. Expect crossing GATE at (present GMT + 15.1 minutes) Zulu."

Similar phraseology was used for the SIMOL approaches with path shortening. Specifically upon waypoint SIMOL passage, the following message was communicated. (Numbers in brackets refer to the low speed SIMOL approach):

"ATC clears Gulfstream N71CR to Stapleton Airport via SIMOL RNAV arrival. Turn direct to TURN 2 10 nmi prior to APRCH. Slow to 180 [110] knots 7 [1.5] nmi prior to TURN 2. Expect crossing GATE at (present GMT + 10.27 [17.3] min) Zulu."

For the SIMOL with delay fan, the following two communications were issued:

"ATC clears Gulfstream N71CR to Stapleton Airport via SIMOL RNAV arrival. Reduce airspeed to 210 [110] knots 3 [1.5] nmi prior to TURN 2. Expect crossing GATE at (present GMT + 11.3 [18.6]) Zulu."

Prior to TURN 2, the delay fan was communicated as follows:

"ATC reclears N71CR from TURN 2 to LOCAL via AFFIX. Turn direct to LOCAL 1.5 nmi prior to AFFIX. Expect crossing GATE at (prior time + 0.6 [1.1]) Zulu."

No additional ATC communications were given. No attempt was made to optimize phraseology.

5.2.3 Cockpit Procedures

The air carrier pilots were instructed to modify their RNAV flight plans as soon as possible following reclearance. The 4D system had the nominal STAR prestored in the flight plan. Pilots were told to minimize final time errors and remain on the nominal flight schedule by observing the EARLY/LATE display and following the airspeed commands. Because of IAS instrument errors, IAS commands could be flown more accurately by zeroing the SLOW/FAST needle indicating TAS error or by zeroing EARLY/LATE time error.

To retain 4D control while flying the delay fans, direct-to procedures were not used by the pilot but the impromptu turn point was entered into the flight plan. If the delay fan were entered, the path as seen by the computer would be to the delay fan waypoint instead of to the turn point prior to the waypoint. As a result, the commanded airspeeds while flying to

the delay fan waypoint would have been higher than desired (to eliminate the effects of the increased distance expected to be flown). After the direct-to procedure was performed, the correct path would be known by the system and proper commands displayed. As a result, when flying delay fans that were commanded by impromptu direct-to procedures, it would be necessary to fly open loop speed control over the initial leg, and command the direct-to at the precise distance. It was therefore easier mentally and procedurally to enter the turn point for the delay fan into the flight plan and then fly closed loop path and speed control over the entire flight.

For the low cost system experiments, closed loop speed control was used only on the last leg to the time control waypoint GATE. The approach speeds flown to the last leg were the nominal speeds for each leg. On the SIMOL approach the final leg is of sufficient duration to null the expected initial timing errors; on the BRAND approach, the leg is too short. As a result, the heading intercept localizer capture technique developed in the first phase was retained in this phase. This procedure works as follows. While the aircraft is flying heading to intercept the final approach course, the time control system is providing speed commands and early/late data based upon the aircraft distance D to GATE (figure 5-9). The algorithm assumes the straight line distance to GATE because GATE is the TO waypoint under the stated conditions. If the aircraft is actually on schedule, the early/late display would indicate slightly early because D is less than the actual path distance; the apparent error reduces to zero as the final approach course is captured. With this procedure, the total duration of closed loop time control is roughly three times that under the final leg alone.

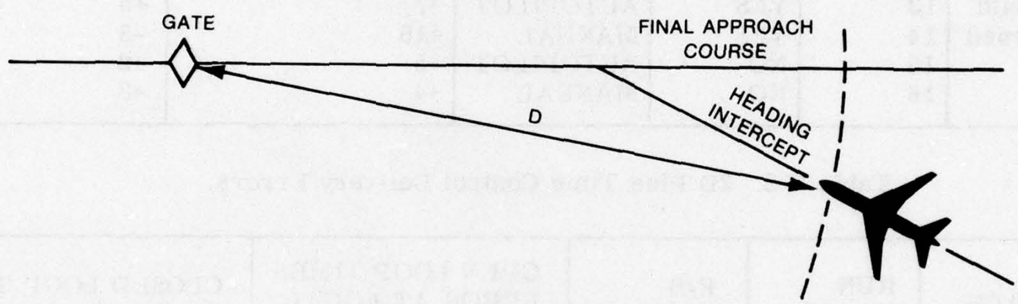


Figure 5-9. Intercept Geometry.

5.2.4 Run Tabulation and Analysis

A total of 24 time control experiments were flown using the BRAND and SIMOL approaches; 16 utilized the 3D/4D equipment and 8 utilized the 2D+ time control equipment. All the latter approaches were flown manually while half the former were flown manually and half were flown autopilot coupled. A tabulation of the approaches including significant parameter variations is shown in tables 5-1 and 5-2. The parameters in the tables are defined as follows:

a. F/S Display

Yes implied that the FAST/SLOW display needle on the flight director was being driven with the difference between commanded airspeed and actual airspeed. Full scale deflection was equal to 10 knots.

Table 5-1. 4D System Delivery Errors.

APPROACH	RUN NUMBER	F/S DISPLAY	CONTROL	TIMING ERROR AT LOCAL OR INTRM (s)	TIMING ERROR AT GATE (s)
BRAND					
With base	1	YES	AUTOPILOT	-2	+2
offset	2	YES	MANUAL	+3	-2
	3	NO	AUTOPILOT	+7	-2
	4	NO	MANUAL	+7	+2
With delay	5	YES	AUTOPILOT	+1	+1
fan	6	YES	MANUAL	+11	+2
	7	NO	AUTOPILOT	+2	-4
	8	NO	MANUAL	+8	-1
SIMOL					
With delay	9	YES	AUTOPILOT	+1	-5
fan	10	YES	MANUAL	+1	-1
	11	NO	AUTOPILOT	-1	-1
	12	NO	MANUAL	+1	+2
With path	13	YES	AUTOPILOT	+7	+5
shortened	14	YES	MANUAL	+15	-3
	15	NO	AUTOPILOT	+5	+2
	16	NO	MANUAL	+4	+3

Table 5-2. 2D Plus Time Control Delivery Errors.

APPROACH	RUN NUMBER	F/S DISPLAY	OPEN LOOP TIME ERROR AT LOCAL OR INTRM	CLOSED LOOP TIME ERROR AT GATE
BRAND				
With base	17	YES	-1	0
offset	18	NO	+4	0
Nominal	19	NO	+3	-5
	20	YES	+2	+16
SIMOL	21	YES	-18	0
With delay	22	NO	-6	-1
fan				
With path	23	NO	-6	+6
shortened	24	YES	-6	0

b. Control

Autopilot implies autopilot control of lateral and vertical steering while manual implies manual flight director steering.

c. Timing-Error

This is the difference between nominal scheduled time and actual time with positive implying early.

Histograms of the timing errors are shown in figures 5-10 and 5-11. Timing errors at LOCAL (for the SIMOL approach) and at INTRM (for the BRAND approach) represent timing errors at waypoints just prior to final approach spacing. The errors are significantly less than the errors experienced in the earlier 3D/4D study (ref 7). The 4D system errors were reduced for $[\mu = -0.5, \sigma = 9.7]$ to $[\mu = 4.4, \sigma = 6.2]$ where the tupplet $[\mu, \sigma]$ represents the mean and standard deviation in seconds. It was felt that the new time control algorithm was smoother throughout the approach so that the pilot actually tracked the command instead of filtering the command via a built-in lag. Basically the commanded airspeed in the phase 1 experiments indicated a large cyclic error, while in this phase a cyclic error pattern was unnoticeable and the airspeed commands appeared to be monotomically decreasing (as they should). In addition, the present simulation did not include any wind shear experiments and hence wind estimation errors were not biased.

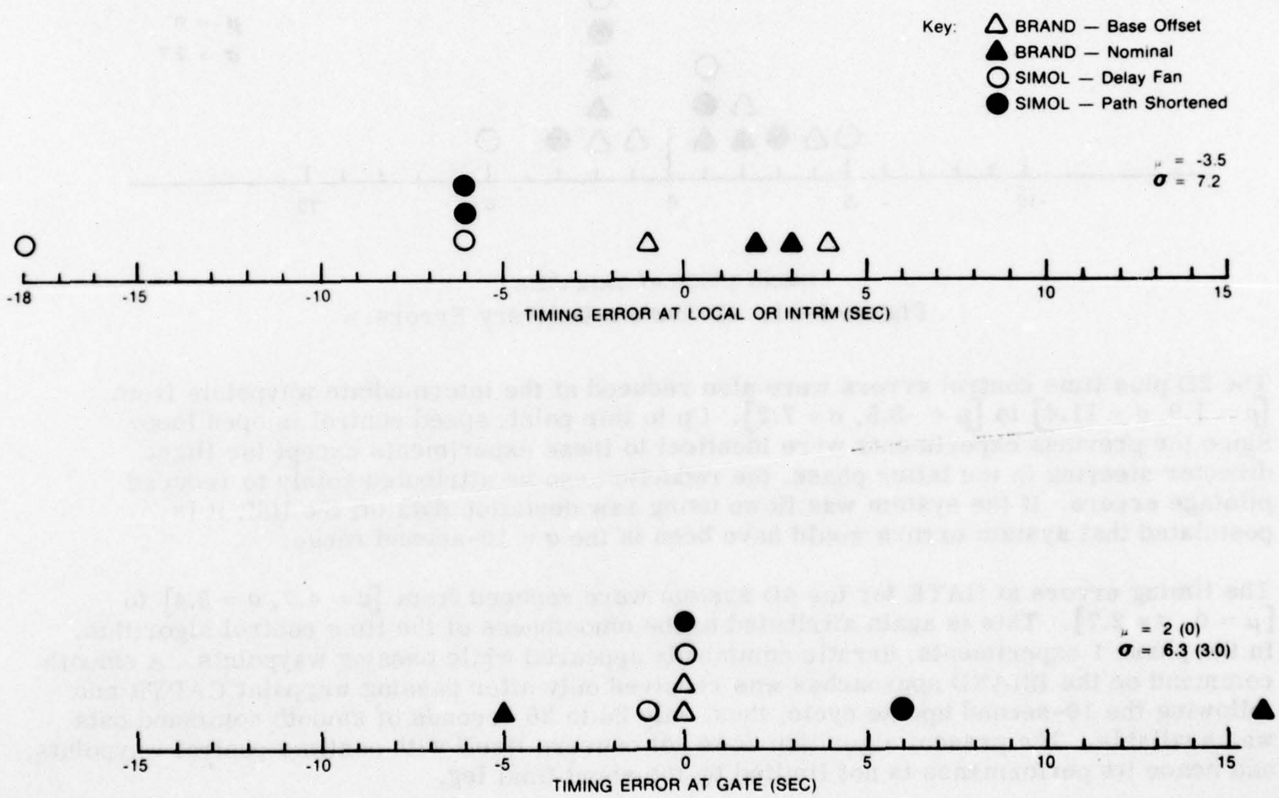


Figure 5-10. 2D Plus Time Control Delivery Errors.

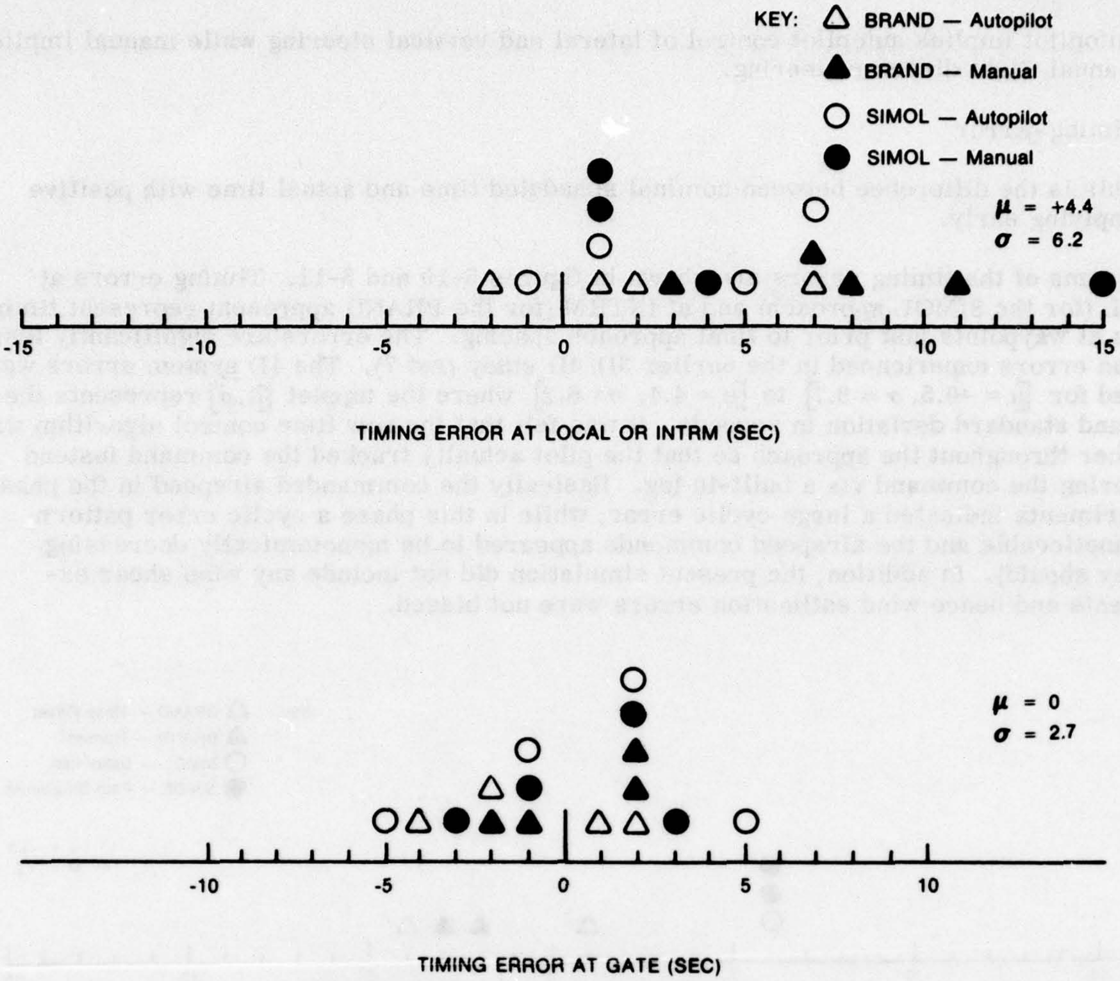


Figure 5-11. 4D System Delivery Errors.

The 2D plus time control errors were also reduced at the intermediate waypoints from [μ = 1.9, σ = 11.4] to [μ = -3.5, σ = 7.2]. Up to this point, speed control is open loop. Since the previous experiments were identical to these experiments except for flight director steering in the latter phase, the reduction can be attributed solely to reduced pilotage errors. If the system was flown using raw deviation data off the HSI, it is postulated that system errors would have been in the σ = 10-second range.

The timing errors at GATE for the 4D system were reduced from [μ = 4.7, σ = 5.4] to [μ = 0, σ = 2.7]. This is again attributed to the smoothness of the time control algorithm. In the phase 1 experiments, erratic commands appeared while passing waypoints. A smooth command on the BRAND approaches was received only after passing waypoint CAPTR and following the 10-second update cycle; thus, only 26 to 36 seconds of smooth command data was available. The present algorithm does not concern itself with nontime control waypoints, and hence its performance is not limited by the short final leg.

The timing errors for the 2D plus time control system were altered from [μ = 4.4, σ = 6.8] to [μ = 2, σ = 6.3]. Because of the limited sample size, no statistical difference is postulated. This is expected since the final legs are of sufficient duration to null out the initial timing

errors and the time control algorithm was identical in both experiments. On the final leg crosstrack errors do not result in along-track errors (that is, following a turn) and hence flight director steering data does not aid time control performance. It is interesting to note that if the anomalies are removed from the latter data the statistics change from $[\mu = 2.1, \sigma = 3.7]$ to $[\mu = 0, \sigma = 3.0]$ again showing no significant differences considering the sample population of 14 and 7, respectively, in Task 1 and 2 experiments.

In both the former and the latter 2D plus time control experiments, the anomalies were the result of pilot's noncompliance with prescribed procedure. In the 16-second early situation the pilot did not fly a heading intercept to localizer but flew an RNAV intercept. As a result the GATE waypoint, course in, and desired time of arrival were entered less than 2 nmi prior to GATE. At the 90-knot approach speed, less than one minute of flight time remained after all the data was entered. Since the approach was early and the final approach speed was limited to 70 knots, the error could not be eliminated. This situation again points out the need to maintain time control over a significant flight duration in order to null the final timing errors. About 10 seconds of error can be removed per one minute of flight time. If errors are allowed to build up beyond this, greater approach lengths must be used.

From the tabular data it can be seen that there does not appear to be any significant difference between runs with FAST/SLOW analog data on the ADI and without the data. While this is true in simulated performance, in practice a large difference is predicted. The pilots almost never looked down on the CDU with F/S on the ADI, resulting in a significant decrease in workload. Nominal speed changes over a leg were easily monitored without the need for an alert light. Fast/slow was the basic display used both far out in the approach (less sensitive to small velocity changes than EARLY/LATE) and near the GATE provided approach speeds were not violated. While EARLY/LATE was helpful in the latter region as a performance measure, FAST/SLOW was still the more adequate command display. Both pilots recommended this display as the primary time control display.

There was no appreciable difference in delivery errors at the GATE under autopilot or manual (flight director) control. The workload was low enough for an experienced pilot to manage closed loop control of path and speed, given the present information. However, it is possible to stay closer to the nominal 4D path over the entire approach while under autopilot control as workload goes down appreciably. The pilot can then temporarily override the speed control commands when off nominal to return to the nominal speed profile. For example, assume that the nominal leg speed is 210 knots, the commanded and actual airspeeds are 205 knots (and hence early/late is 0). This implies that the aircraft is slightly ahead of schedule (205 commanded vs 210 nominal), but by maintaining the present speed reduction the aircraft will cross the time fix on schedule. If the indication is steady (implying wind shear of navigation errors are not disruptive), the pilot can return to nominal schedule by further reducing his speed (early/late will temporarily indicate LATE) until the commanded airspeed is 210 knots at which time actual airspeed is increased to 210 knots and LATE returns to zero. The aircraft is now predicted to be back on schedule both at the time fix and also at its present position. The additional workload associated with this activity was only possible during autopilot controlled experiments.

Two additional items that were deemed acceptable during this phase were the insertion of speed data and flying RNAV base leg extensions. The speed entries were limited in number to the actual number of different speeds used during the approach. The speeds were entered at existing 2D or 3D waypoints - additional waypoints need not be created. Hence navigation was maintained to the 2D or 3D waypoints reducing both pilot workload and blunders during data insertion and navigation.

Base leg extensions were previously flown by means of leg-at-a-time offsets for the 4D system and by parallel offsets for the 2D system. When shallow course intercepts were flown with the 4D system, offsets on two legs were required. This was cumbersome and blunder prone. The use of a single base offset entry without the need to specify right or left resulted in an acceptable base offset procedure. For the low-cost sytem, the offset on the first leg was flown and a heading flown on the next leg. Acceptable performance was achieved in the Task 1 experiments, if distance to wayline information and not distance to (parent) waypoint information were used for turn anticipation. Acceptable performance was also reached in this phase by providing distance to (offset) waypoint data on the HSI.

Performance of the 2D system in executing delay fans via impromptu direct-to procedures was also acceptable. This was attributed to the ability to prestore all STAR waypoints and thereby fly to all waypoints. Similar conditions were noticed during the first phase 10-waypoint system experiments in contrast to the 2-waypoint system experiments. When ATC commands such as "turn direct LOCAL 1.5 nmi prior AFFIX" are given, navigation should be to AFFIX so that the pilot is only required to mentally add a turn anticipation distance to 1.5 nmi prior to calling up and flying to LOCAL and zeroing crosstrack deviation. Navigating from a waypoint to AFFIX requires subtracting the sum of 1.5 nmi and the turn anticipation distance from the leg distance usually resulting in overshooting the desired course as the turn anticipation number is forgotten. It is therefore concluded that proper execution of delay fan flights using impromptu direct-to procedures requires flying to both the delay fan waypoint and the direct-to waypoint.

5.3 ILS EXPERIMENTS

5.3.1 ILS Capture Conditions

A limited real time cockpit simulation was also undertaken to check out and evaluate the performance of the ILS capture tracking algorithms under manual and autopilot control. A total of six different intercept conditions were established, namely 90° captures at 3, 5, and 7 nmi from runway touchdown point, and 10°, 20°, and 30° shallow intercepts to a simulated outer marker 5.4 nmi from runway touchdown point. Figure 5-12 illustrates the plan and profile views of the ILS approach paths. All indicate a vertical descent to localizer capture, an altitude hold to glideslope capture followed by glideslope tracking. All approaches were flown at a nominal approach speed of 120 knots.

Table 5-3 lists the ILS approach conditions along with a yes/no summary of system performance. Strip chart recordings of the approaches 1 and 2 are shown in figures 5-13 and 5-14. The data under "turn initiation" indicates whether the RNAV based steering module or the ILS based steering module was used to initiate the turn. The method for accomplishing this will be described later. The last column indicates if Category II type performance of 35 μA RMS outside of 200 feet and 12 feet RMS within 200 feet of altitude was maintained. For autopilot approaches, no sustained oscillations were allowed or observed. Manual approaches experienced a somewhat cyclic deviation. For these approaches, an RMS value of 35 μA was replaced by a requirement to limit peak excursions within 50 μA beyond 0.75 nmi (200 ft/tan 2.5°) from runway touchdown point. At 120 knots, 0.75 nmi corresponds to a little over 20 seconds or 2 major time divisions on the charts. Runway touchdown point coincides roughly with the glideslope deviation saturation on the charts.

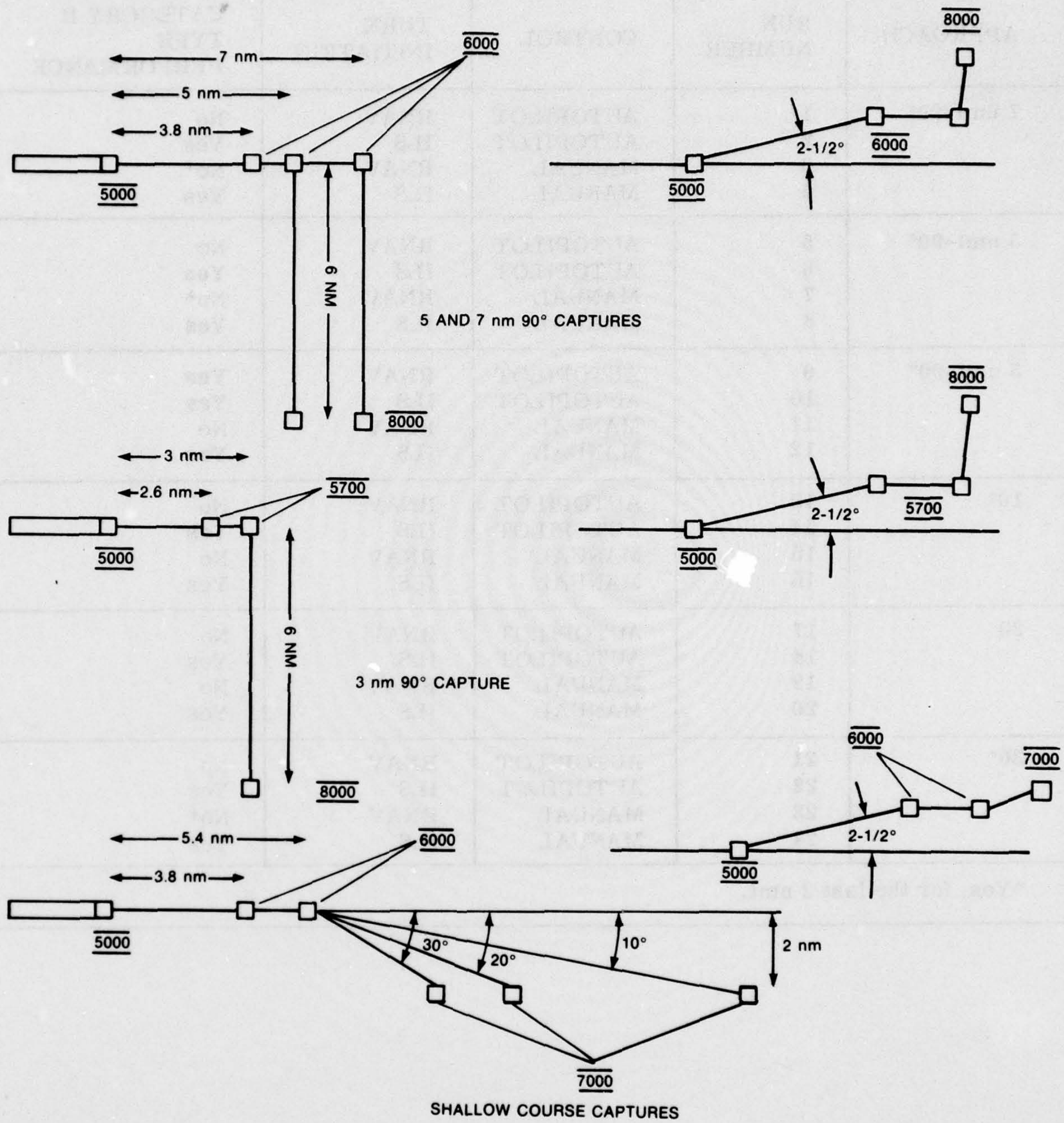


Figure 5-12. ILS Approach Plan and Profile Views.

Table 5-3. RNAV Aided ILS Approach Conditions.

APPROACH	RUN NUMBER	CONTROL	TURN INITIATION	CATEGORY II TYPE PERFORMANCE
7 nmi-90°	1	AUTOPILOT	RNAV	No
	2	AUTOPILOT	ILS	Yes
	3	MANUAL	RNAV	No*
	4	MANUAL	ILS	Yes
5 nmi-90°	5	AUTOPILOT	RNAV	No
	6	AUTOPILOT	ILS	Yes
	7	MANUAL	RNAV	No*
	8	MANUAL	ILS	Yes
3 nmi-90°	9	AUTOPILOT	RNAV	Yes
	10	AUTOPILOT	ILS	Yes
	11	MANUAL	RNAV	No
	12	MANUAL	ILS	Yes
10°	13	AUTOPILOT	RNAV	No
	14	AUTOPILOT	ILS	Yes
	15	MANUAL	RNAV	No
	16	MANUAL	ILS	Yes
20°	17	AUTOPILOT	RNAV	No
	18	AUTOPILOT	ILS	Yes
	19	MANUAL	RNAV	No
	20	MANUAL	ILS	Yes
30°	21	AUTOPILOT	RNAV	No
	22	AUTOPILOT	ILS	Yes
	23	MANUAL	RNAV	No*
	24	MANUAL	ILS	Yes

*Yes, for the last 2 nmi.

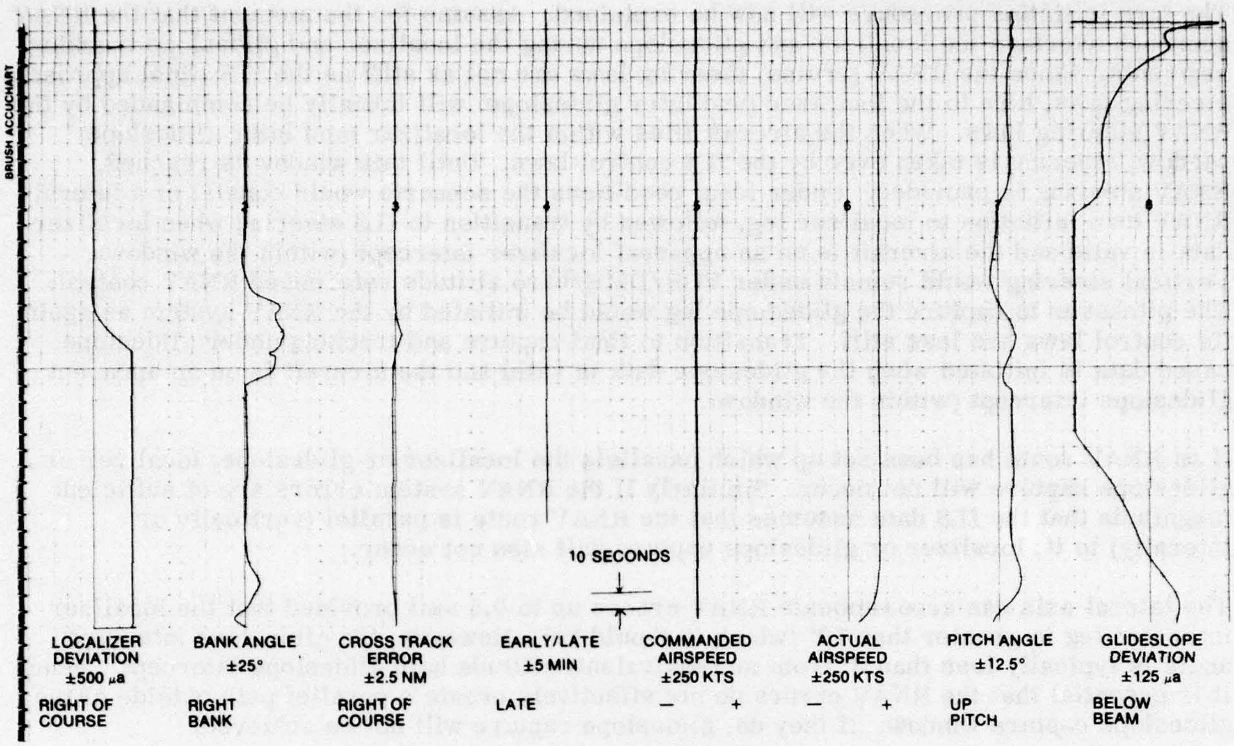


Figure 5-13. RNAV Initiated ILS Captures.

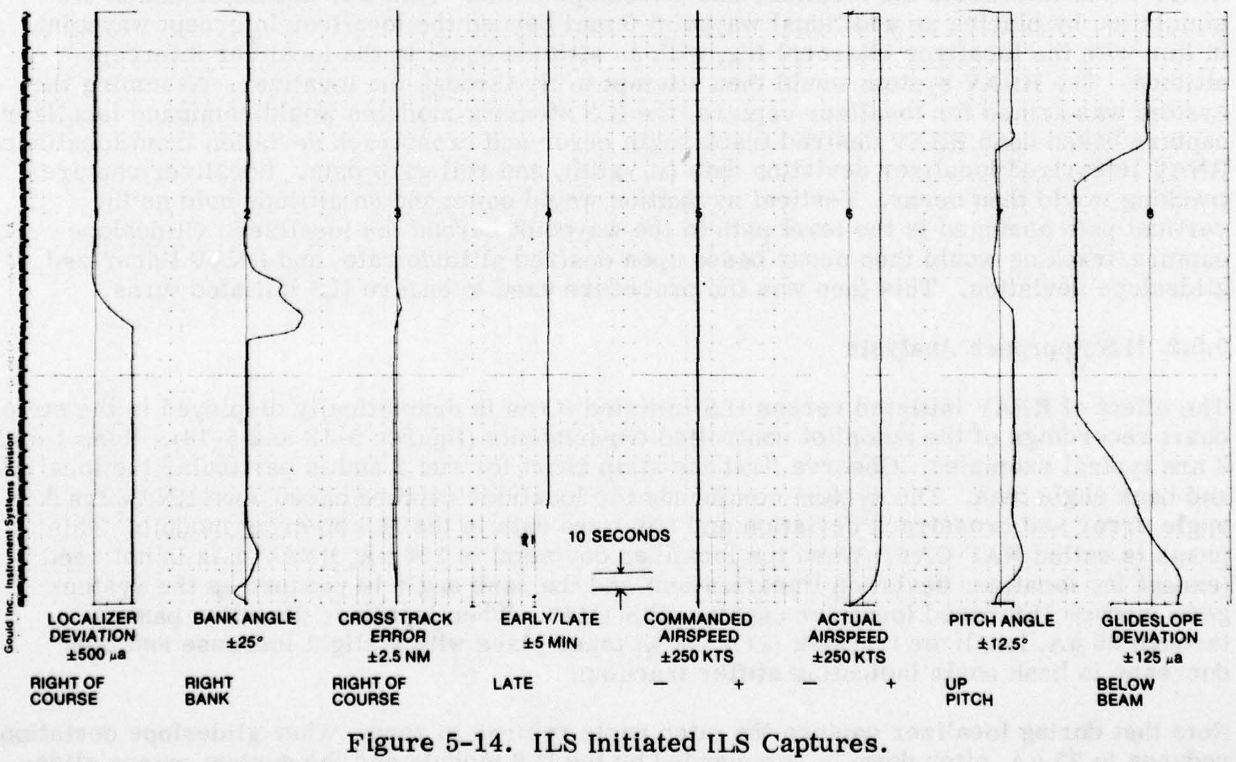


Figure 5-14. ILS Initiated ILS Captures.

The turn initiation procedure will now be explained. Assume for the moment that the RNAV approach overlays the localizer and glideslope during the localizer and glideslope tracking segments. Since the RNAV (cruise) steering laws are not as stiff as the ILS (final approach) steering laws, turn to the localizer (and later glideslope) will initially be commanded by the RNAV steering laws. When the aircraft flies within the localizer (and later glideslope) window, steering is taken over by the ILS control laws. Until this window is reached, RNAV steering is provided. Under ideal conditions the scenario would consist of a lateral RNAV turn initiation to localizer leg, followed by transition to ILS steering when localizer data is valid and the aircraft is on an apparent localizer intercept (within the window). Vertical steering would remain under VOR/DME/baro altitude referenced RNAV control. The pitchover to capture the glideslope leg would be initiated by the RNAV system as again its control laws are less stiff. Transition to final capture and tracking under glideslope based data is initiated when the glideslope data is valid and the aircraft is on an apparent glideslope intercept (within the window).

If an RNAV route has been set up which parallels the localizer or glideslope, localizer or glideslope capture will not occur. Similarly if the RNAV system errors are of sufficient magnitude that the ILS data assumes that the RNAV route is parallel (vertically or laterally) to it, localizer or glideslope capture will also not occur.

The lateral axis can accommodate RNAV errors up to 0.5 nmi provided that the localizer intercept leg is greater than 10° (which it should be). However, the glideslope intercept angle is typically less than 3° from an (equivalent) altitude hold glideslope intercept. Hence it is essential that the RNAV errors do not effectively create a parallel path outside of the glideslope capture window. If they do, glideslope capture will not be achieved.

To ensure localizer and glideslope capture (given the data is valid), it is sufficient that the RNAV route intersects the localizer and glideslope paths. This was accomplished in the simulation by placing an additional waypoint 5 nmi beyond the localizer intercept waypoint in line with the localizer intercept leg, with an altitude equal to the localizer intercept altitude. The RNAV system would then attempt to fly through the localizer. Assuming the system was armed for localizer capture, the ILS steering modules would command localizer capture based upon RNAV desired track angle error and crosstrack deviation from localizer, RNAV linearized localizer deviation data (if valid), and roll gyro data. Localizer capture/tracking would then occur. Vertical navigation would command an altitude hold as the vertical path assumed is the level path to the waypoint beyond the localizer. Glideslope capture/tracking would then occur based upon desired altitude rate, and RNAV linearized glideslope deviation. This then was the procedure used to ensure ILS initiated turns.

5.3.2 ILS Approach Analysis

The effect of RNAV initiated versus ILS initiated turns is dramatically displayed in the strip chart recordings of the autopilot controlled experiments (figures 5-13 and 5-14). Runs 1 and 2 are typical examples. Observe first the strip chart for run 2 and in particular the localizer and bank angle data. The system commands the localizer capture based upon RNAV track angle error and crosstrack deviation and roll gyro data in the ILS steering module. This phase is called NAV CAP. When the localizer deviation is 200 μA, RNAV data is not used (except for localizer deviation linearization) and the bank angle is reduced as the system goes through ILS based localizer capture (ILS CAP). When localizer deviation passes through 25 μA, localizer tracking (LOC TCK) takes place with a slight increase and then decrease in bank angle indicating stiffer tracking.

Note that during localizer capture the pitch angle returns to zero. When glideslope deviation reduces to 25 μA, pitch down is commanded by the ILS module and the system enters glide-slope capture and tracking.

The situation is significantly more complex in Run 1. Localizer capture occurred as follows. The initial bank is commanded by the RNAV system and is beginning to be faded out as localizer deviation leaves the 300 μA saturation. At this point the aircraft has arrived in the localizer capture window and the ILS lateral steering module takes over. The initial control laws are RNAV based but complemented with roll data, which allows for greater stiffness without incurring potential stability problems. A greater bank is therefore commanded at roughly 300 μA (NAVCAP in this example). At 200 μA (ILSCAP) the bank command changes slightly and is being bled off until 25 μA of localizer deviation. At this point localizer tracking takes over and the maneuver is completed. Note that while the smoother RNAV cruise steering laws initiated the turn, the resultant reduced track angle error did not prevent the aircraft from reaching the localizer capture window.

This is not the case in the vertical axis. The pitch down command after localizer tracking is commanded by the RNAV system. The along-track error is so great that the flight path almost parallels the 2.5° glideslope beam. The flight path angle settles to 2°, and the resultant flight path enters the glideslope capture window within 1 nmi of touchdown. At this point an increase in pitch angle is commanded by the ILS glideslope steering module but the system is too close-in to stabilize on the glideslope.

These same conditions were observed during all RNAV initiated autopilot approaches. Under manual steering with flight director guidance, it was possible to trip earlier by observing the standoff in glideslope path and pitch the aircraft up slightly to enter the capture window. However, it was then necessary to pitch down and this oscillatory behavior was difficult to arrest while maintaining control over both axes. In contrast, when the glideslope initiated the final pitchdown, all autopilot and manual approaches exhibited Category II type tracking performance under the simulated conditions.

The only approach under autopilot control in which the RNAV initiated turn successfully tracked the glideslope was the 3 nmi close-in capture. However, this approach is somewhat of an anomaly. Although the straight line waypoint defined approach assumes a capture from below, the actual capture is from above the glideslope. The aircraft is still turning to capture the localizer when glideslope capture is initiated. Since captures from above have a larger window in order to bleed off excessive vertical speed, a glideslope standoff has to be much greater to prevent glideslope capture. In addition, since the RNAV error in this case results in a below beam error, the aircraft would normally be on an intercept path toward the beam and glideslope capture would again be successfully initiated.

While the manual 3 nmi close in capture (test 12) with an ILS initiated turn was judged successful, the aircraft was never stabilized on the glidepath. The aircraft first crosses the localizer about 2 nmi from touchdown at a height of about 500 feet. Glideslope tracking is initiated somewhere in this region. There is little time remaining to look up and line up with the runway beyond this point. The remainder of the ILS turn initiated manual approaches were judged to have acceptable performance.

None of the RNAV initiated turns under manual flight were judged to meet the 50-μA peak excursion criterion beyond 0.75 nmi. It would be argued, however, that test 3, 7, and 23 (or 1/2) of these approaches met the criterion. When the standoff was noticed (via HSI glideslope deviation), flight director vertical steering (using RNAV data) was temporarily ignored and a glideslope intercept forced. Glideslope capture was then initiated under flight director guidance (now using ILS data in both channels) resulting in acceptable performance. Two of the three totally unsuccessful approaches were the first approaches flown by each pilot. At this time the standoff and its effects on glideslope capture were observed. For the following approaches the pilots formulated their procedure to limit initial pitchdown and force glideslope capture. The other unsuccessful approach was the 3 nmi 90° close-in capture which does not leave any tolerance for error.

Conclusions

The first phase of the 3D/4D system study verified that time control could be successfully integrated into the terminal area with considerable performance benefits. Modifications to the original design were suggested to improve operating procedures and extend time control in final approach while under RNAV and ILS guidance. These goals were incorporated into the 3D/4D system developed. While the viability of the approach will be proven under actual flight conditions, the limited real time cockpit simulation presented the following conclusions:

6.1 3D RNAV PROCEDURES IN FINAL APPROACH

a. Both 90° and shallow capture angle base legs can be flown under RNAV guidance with a limited addition to basic RNAV capabilities. A major requirement is to standardize on a limited set of approach procedures.

b. Transition to localizer guidance can be maintained while under RNAV navigation. Either dual VOR/LOC or independent VOR and LOC receivers are required, as guidance from both sources is required.

c. Transition from RNAV to localizer steering can be accomplished automatically under autopilot control. Care must be maintained so that the RNAV system errors do not command too early a turn.

d. 90° captures to the ILS 3 nmi from threshold are unacceptable under manual or autopilot control as there is no margin for error. RNAV aided 90° captures 5 nmi from threshold may be acceptable.

6.2 TIME CONTROL PROCEDURES

a. Controlling time of arrival to the time-fix by means of speed deviations over the entire distance results in acceptable ride qualities under VOR/DME/TAS based RNAV guidance.

b. The most preferred method of displaying commanded speed information is display of deviation from commanded IAS on the FAST/SLOW needle of the flight director. Display of commanded airspeeds on the IAS indicator or CDU is of secondary importance.

c. Time control can be maintained while capturing and tracking the localizer by both leg-at-a-time and multiple leg systems. The former can obtain sufficient time control data while flying a heading intercept.

d. Final delivery errors under 5 seconds (1σ) are achievable using 4D time control procedures. Care must be exercised so that the final leg is of sufficient length to null the initial delivery errors.

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